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DESIGN FEATURES AND THEIR AFFECT ON HIGH PERFORMANCE FILL

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The studies and conclusions reported in this paper are the results of the author's own work. The paper has been presented and reviewed by the Cooling Technology Institute, and approved as a valuable contribution to cooling tower literature.

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Design Features
of
Cross-Fluted Film Fill
and
Their Affect on Thermal Performance

by

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Abstract

In the design of a high performance cooling tower fill, many design features must be considered to produce optimum performance. This paper will show laboratory test data and detail the affect of the following items on fill performance: Flute geometry (cross-fluted, offset-flute, vertical flute); Cross-flute angle, Microstructure (step, rounded, none); Material (PVC & polypropylene); Module depth (12" layers vs. 24" layers); Tip design (alternate tips vs. straight tips).

The data reported in the paper will be collected utilizing a state-of-the-art laboratory counterflow test cell.

Introduction

Film fills have been used in the design of cooling towers from the very beginning of cooling tower construction. The precursor to modern plastic fills was any thin flat material used in common construction such as wooden planks laid as inclined platforms (figure 1) or oriented on edge (figure 2). Galvanized steel was also used. These materials were not rot or corrosion resistant and would need replacement only after a few years in service. Hollow thin bricks were used to extend life but were heavy and required strong structural supports (figure 3) which added cost.

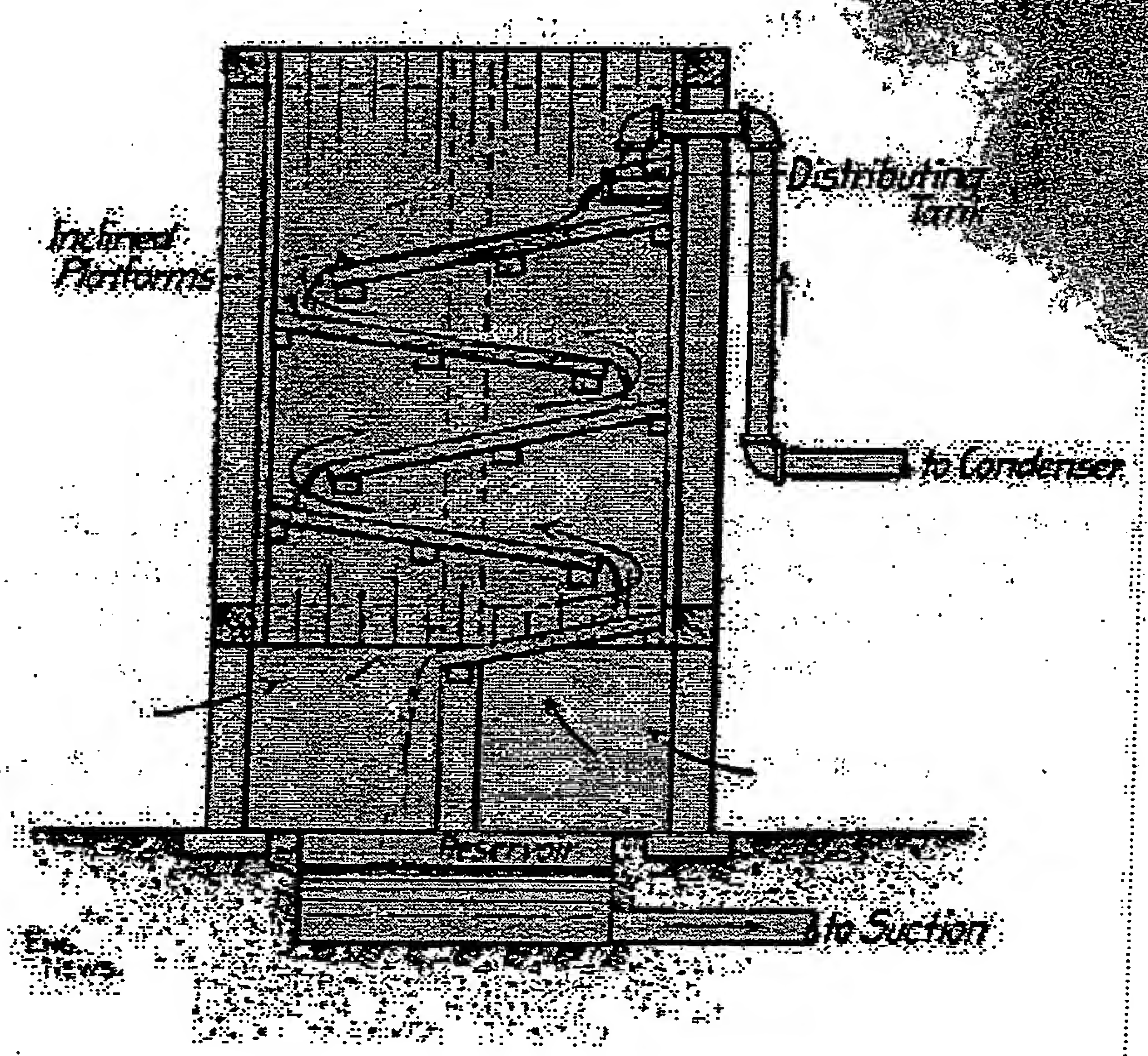

Figure 1. Early form of film fill.

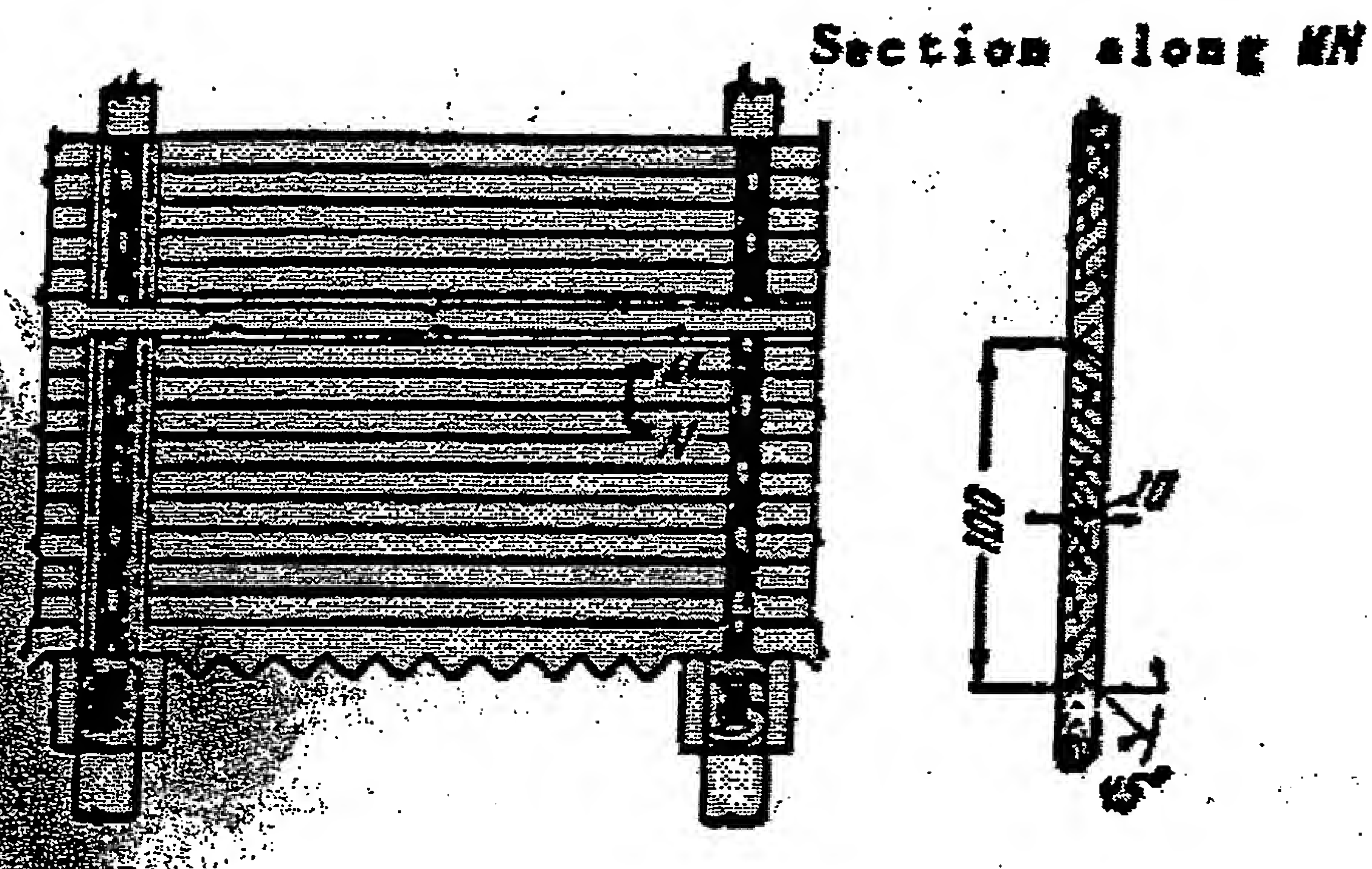

Figure 2. Thin wooden boards stacked in deep sections as film fill. Note early form of special drainage tips.

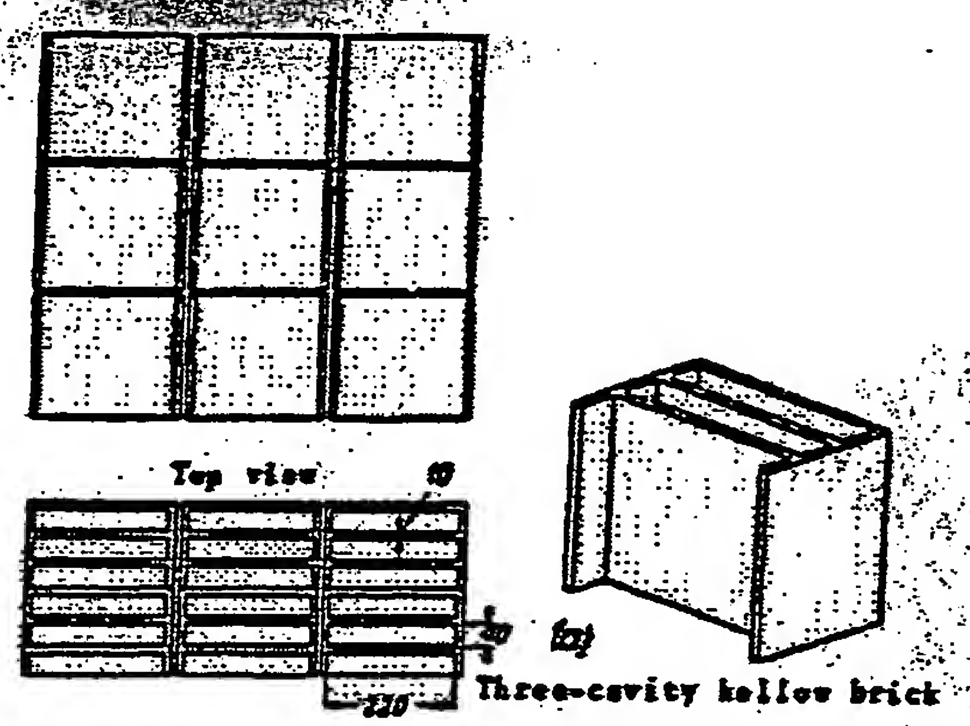

Figure 3. Ceramic brick film fill circa 1949.

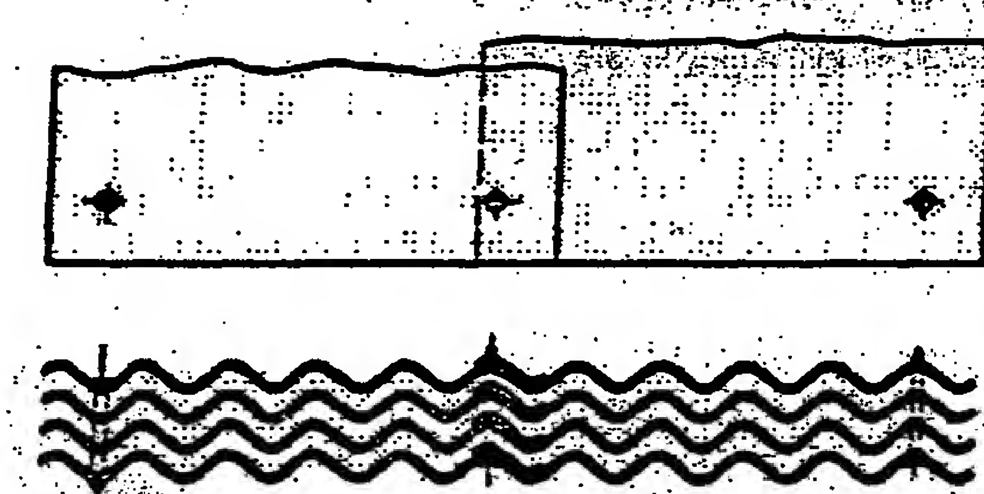

Figure 4. Corrugated asbestos cement board film fill.

An improvement over these designs as early as 1936 used corrugated plates of asbestos cement board (ACB) in deep fill sections (figure 4). The idea of combining corrugated and flat sheets together was developed by Carl Munters and patented in 1957. In his patent, Carl Munters envisioned the flute heights to be "1-7mm or even more". In 1963 Arthur Kohl and Alfred Fuller of Fluor Products Company were granted a patent on a 'pack' where all sheets were corrugated (although vertically) thereby maximizing the heat transfer surface area (HTSA). This patent showed a significant development in that the inventors stated that 'it has been found that the nominal diameter of the openings should be about ½" to 1" (figure 5). This recognizes the essential fact that small flute diameters, although having very high HTSA were of limited use due to the very high-pressure drop.

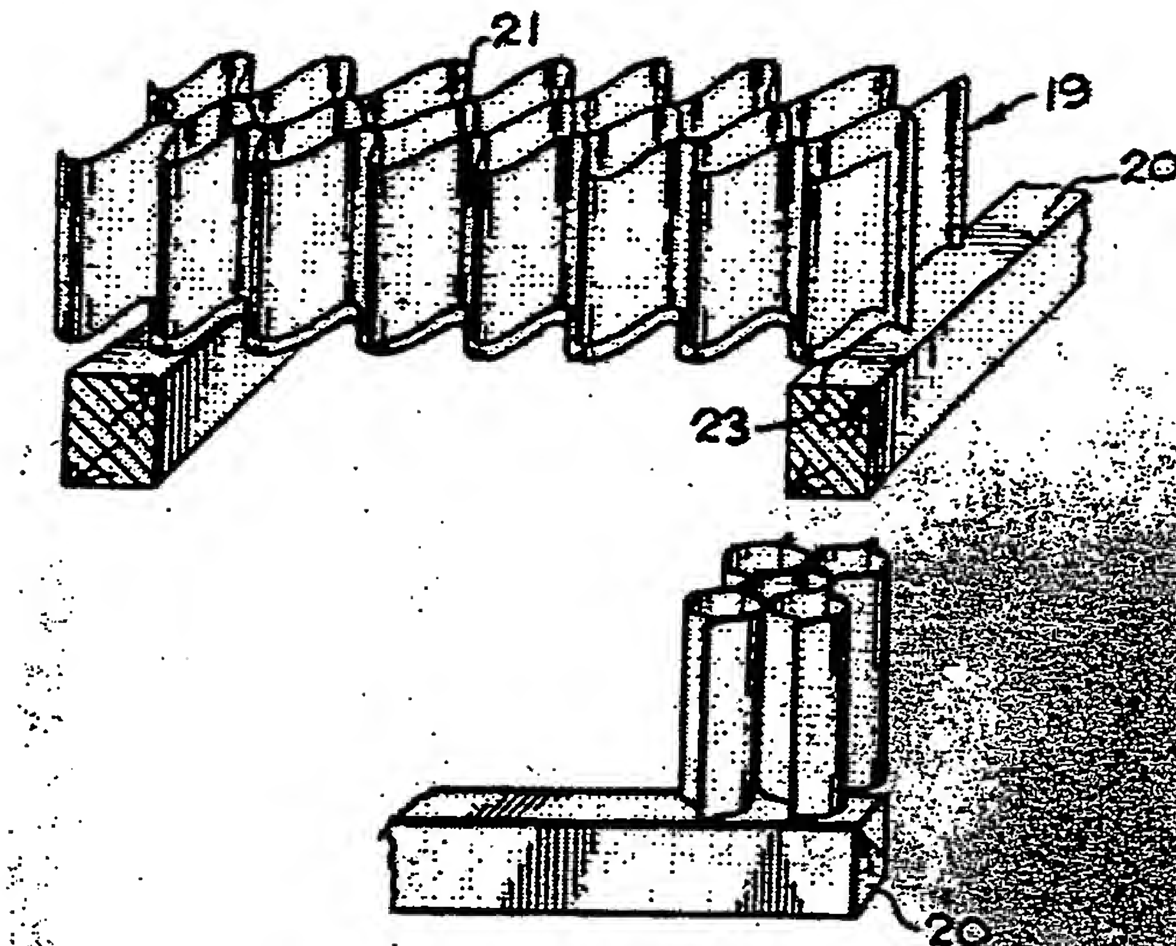

Figure 5. Fluor's "film pack", first use of fully corrugated sheets.

It wasn't until the invention of the cross-fluted design by S. Bredberg patented in 1966 (assigned to Carl Munters Co.) that low-profile, highly efficient fill sections were realized (figure 6). The flute angle was not specified in the patent keeping it as broad as possible. In early 1964 the experimenters tested packs with flute angles of 20°, 30° & 40° to find the best combination of thermal performance and pressure drop and settled on 30°. It is also interesting to note that the original design was conceived for use in crossflow applications.

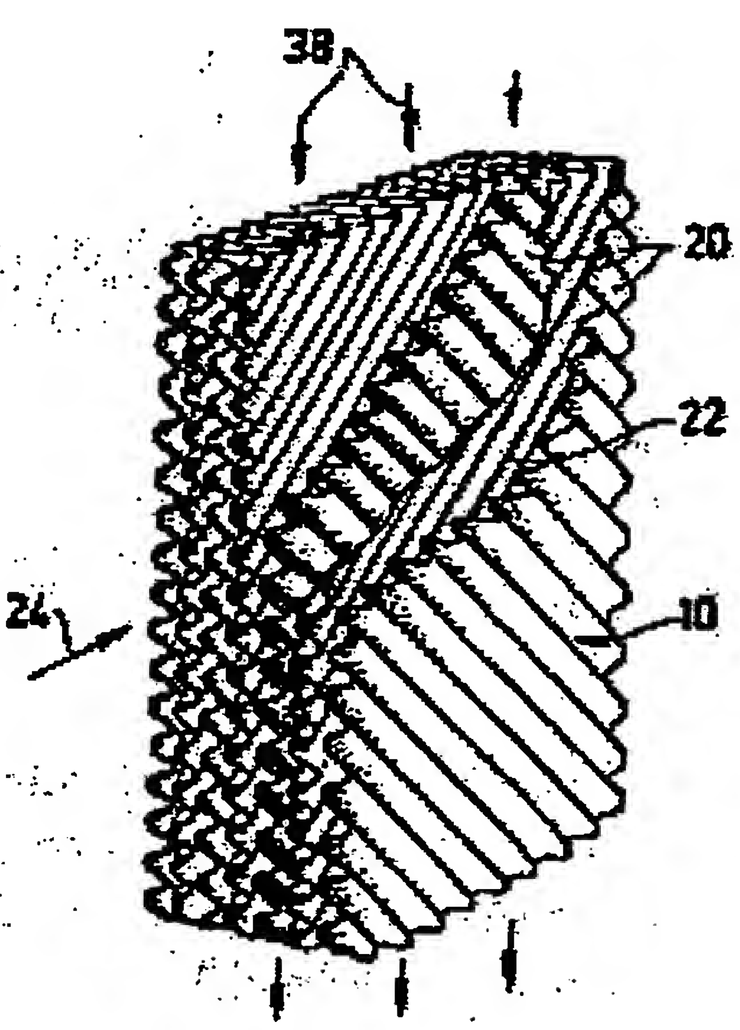

Figure 6. Cross-fluted fill from Bredberg's 1966 patent.

The idea of corrugating sheets was one of practicality since the flat sheets tended to warp when wetted. Packs made with corrugated sheets had many advantages:

- They would be strong by the very nature of their shape, so lightweight and inexpensive materials could be used in their construction.
- The corrugations would be easy to shape.
- Packs would be easily constructed.

The design objective of a fill designer is to produce a product with the highest possible heat transfer potential, the least amount of air-side pressure loss, using the best material available and by the simplest manufacturing method. For the highest possible heat transfer, the packing must maximize its surface potential by allowing complete wetting and provide maximum air-water contact. For the lowest possible airside pressure loss the cooling must occur while minimizing the mechanical energy lost by the air. The best available material will allow the fill to be completely compatible with all potential cooling tower water and water treatment chemicals, corrosion resistant, flame retardant, lightweight, and low cost. The simplest method of manufacturing will allow the product to be made with high productivity, low waste, and of highest quality.

With the introduction of plastics as a suitable material for film fill, designers have complete freedom to explore all the design possibilities to extract the most out of every square inch (or square cm) of this versatile material for the film fills surface.

The Project Scope:

This paper will provide an in-depth examination of the features of cross-fluted film fills and their affect on thermal performance and pressure loss by the systematic variation of each design feature. Also discussed will be the relative performance of each flute type based on testing of representative samples.

Specific features investigated:

- Microstructure type (step, rounded, none)
- Flute type (cross-flute, offset-flute, vertical-flute)
- Flute angle (30°, 31°, 34°)
- Tip design (alternate vs. straight)
- Module depth (12" vs. 24")
- Materials of construction (PVC vs. polypropylene) & affect of aging

Packs representing each feature variation were created and tested to produce curves of thermal performance in the form of KaV/L vs. L/G, and corresponding pressure loss curves in the form of pressure drop vs. air velocity. Although important to the tower designer, direct comparisons and conclusions are difficult to reach by use of these curves alone. It is in this context that the concept of 'air horsepower' will be employed to make such direct comparisons. Air horsepower is the theoretical power required to move a required amount of air against a given pressure drop at 100% total efficiency and can be considered the minimum power required to move the air through the given pressure drop. This concept allows us to compare fills of different thermal & pressure loss characteristics directly. This is useful since a given design may have a low KaV/L value requiring high air volume but also a correspondingly low-pressure loss. By using the concept of air horsepower for each design, and recognizing that the one-third root of the ratio of these calculated power values yield tower capability, we can easily see the total affect of heat transfer and pressure drop for each feature evaluated. See Appendix 2 for a sample calculation showing details of the methodology.

The Test Rig

The fills were tested in Brentwood Industries twin counterflow test cells located in our Reading, Pennsylvania (USA) facility. The detailed description and drawing of the facility can be found in Appendix 1. To summarize: each test cell has an internal dimension of 24" x 24" (610mm x 610mm) in plan and can fit up to 5' (1525mm) of fill. Heat is supplied by a controlled hot water source of constant temperature. Water is sprayed onto the fill using a full cone square patterned sprayer with water flow measured by magnetic flowmeters. Air is measured by averaging pitot tubes, fill pressure loss is measured by upstream and downstream static 'H' taps and temperatures are measured with platinum RTD's. All measurements are collected via data acquisition hardware on a 10-second cycle and displayed and analyzed using in-house developed software. An exact heat balance ratio (HBR) is calculated using the measured exit air temperature and individual data points are thrown out if the HBR's do not fall within 98% to 102%.

Test Protocol

In all tests 4' (1220mm) of fill was investigated. The fill was placed in the tower in an alternating fashion to provide the best possible distribution of water. The test is conducted by adjusting the waterflow from the low waterloading (q/a) setpoint and the airflow is allowed to vary from 300 ft/min (1.5 m/s) to 700 ft/min (3.5 m/s) in steps of 200 ft/min (1 m/s). Data is collected for a minimum of 15 minutes at 10-second intervals when the temperatures reach steady state and the heat balance ratios consistently read between 98% to 102%. The water loading is then adjusted to the next set point and the process is repeated. Three air velocity and three water set points, 3.5 gpm/ft^2, 6 & 8 (8.5 m^3/hr/m^2, 15 & 20) are used to develop the full set of curves. Characteristic curves and pressure drop plots are created from the resulting data. The KaV/L analysis used is the standard CTI methodology including the 4-point Tchebycheff integration and fit to the equation $KaV/L = C(L/G)^{Slope}$. The pressure drop data is fit to the standard form of $DP = C0vel^{C1}+qa(C2vel^{C3})$.

Features Evaluated

Microstructure

Microstructure is the term we use to describe the designed-in small-scale deformations on the sheet's surface that provides both thermal and structural advantages to the finished packs. Structurally the flutes are stiffer with added microstructure. Thermally, it provides the following important functions:

1. Remixes the water film to refresh the air-water interface.
    - The heat transfer process occurs at the air-water interface, the exact boundary between the surface of the water film and the laminar sublayer of the air directly adjacent to it. This layer reaches equilibrium quickly and the microstructure tends to remix the relatively thick water film thereby renewing the interface.
2. Enhances wetting (surface utilization).
    - Microstructure tends to disperse the water film laterally (90° left and right from the flow direction) thereby wetting more surface. The goal is to have all the heat transfer surface area (HTSA) wetted (100% surface utilization).
3. Increases the HTSA of the pack.
    - Typical rounded microstructure can increase HTSA by up to 3%.

Three different designs were investigated and compared to a pack without microstructure (smooth). Step microstructure is found in many cross-fluted designs and tends to increase KaV/L value at the expense of developing high airside flow resistance. Rounded microstructure is found in most early designs and performs its intended function without the increase in airside pressure drop. Standard microstructure is the design currently used in CF-1900. The microstructure geometry can be visualized in figure 7 below.

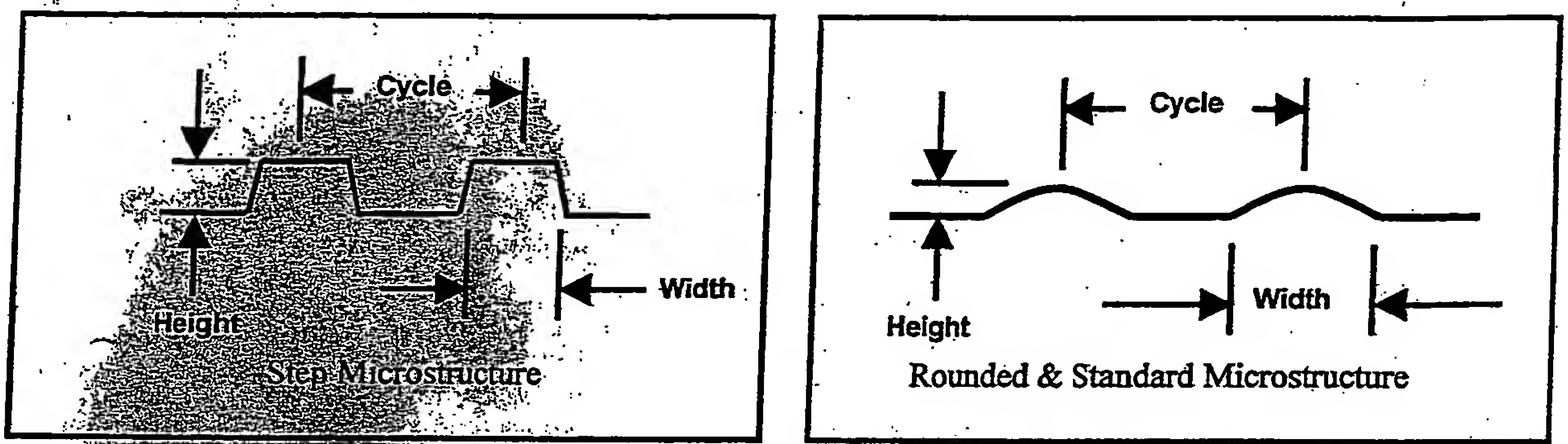

Figure 7. Step and Rounded Microstructure

The results of the microstructure tests are shown in figures 24 through 27. The step microstructure tends to increase the KaV/L value of the fill, but the resistance to airflow is increased significantly. This is most likely due to the increase of surface roughness since the step microstructure pressure losses are higher than the other microstructures studied, at high waterloadings and dry.

The affect of the microstructure falls off as the water rate increases. This is caused by the thicker water film generating ripples, as though microstructure was present. Also, the higher water rates promote more complete wetting of the fill's surface. Figure 27 shows the tested result that the standard microstructure and step microstructure improves fill performance at the lower water rates but at the higher rates the step microstructure lowers fill performance due the marked rise in pressure drop. In fact, the step microstructure performs worse than the non-microstructure pack at waterloadings above 7.5 gpm/ft^2.

Flute Type

There are three fundamental types of flute geometry in use today in the design of film fills for cooling towers:

1. Cross-flute (CF) designs (Figure 8)
2. Offset-flute (OF) designs (Figure 9)
3. Vertical-flute (VF) designs (Figure 10)

Cross-flute designs have a long history in the cooling tower market. These designs are noted for their high efficiency and moderate pressure loss and have been in use in cooling towers since the early 1960's. Early packs include Munters' CF-12060, CF-19060, Brentwood's CF-1200 and CF-1900 and Marley's MC-67.

Offset tube designs were developed later, and are highly efficient. Instead of mixing points developed by the crossing of alternate flutes, the mixing occurs by the vertical offset flutes that

split and rejoin the air and water streams. Offset-flute designs include Hamon's ANCS (CoolFilm) and Balcke-Durrs's FB-20.

Vertical-flute designs are a more recent development in response to issue of fouling. By virtue of the vertically oriented flutes, water film velocity is increased, maximizing shear stress in the water film, which reduces biofilm attachment. Vertical-fluted designs include Brentwood's VF-5000, VF-3800, VF-19Plus and Hamon's AFNCS (CleanFlow) and Balke Durr's FC-18.

The results of the flute type tests are shown in figures 28 through 31. It can be seen that the offset-flute and cross-flute designs have the highest efficiencies, with the offset-flute designs showing a slightly better efficiency at the lower water rates. This is due solely to the lower developed pressure drop for this design. High efficiency vertical-flute designs typically fall below the efficiencies of the cross-flute and offset-flute designs by virtue of their reduced number of mixing points. This tends to reduce the airside mixing, lowing pressure drop and keeping the heat transfer characteristic low. However, the newer high efficiency VF designs come very close to the CF & OF counterparts via technically advanced microstructure. It is important to note that both VF & OF designs are benefited by the addition of a top 12" (305mm) layer of CF fill to compensate for a imperfect water distribution system, or for distribution system failures.

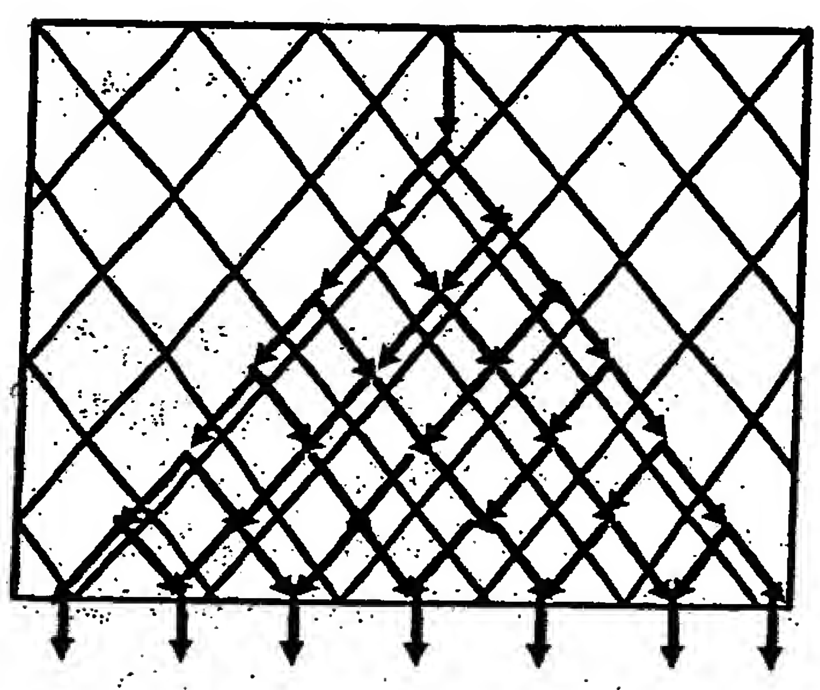

Figure 8. Cross-flute design

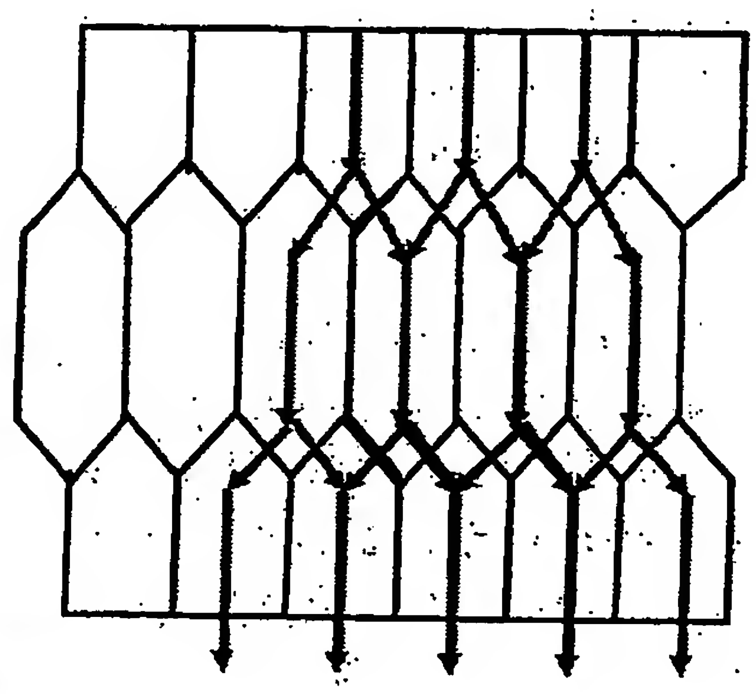

Figure 9. Offset-flute design

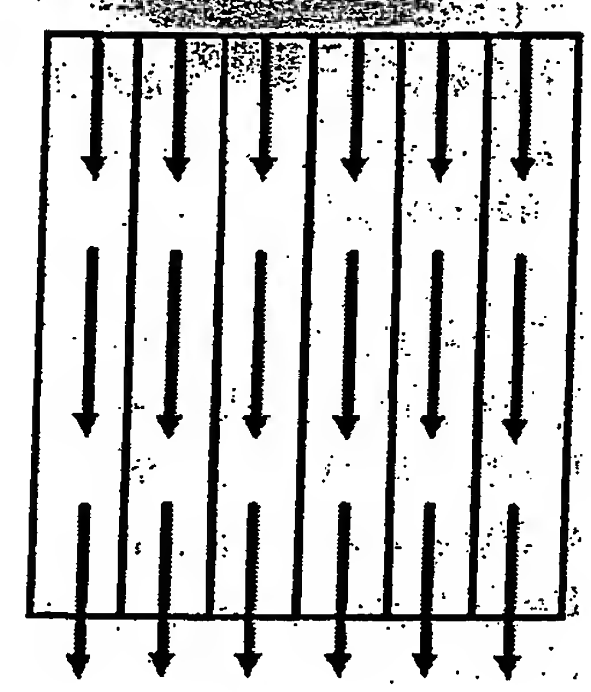

Figure 10. Vertical-flute design

Flute Angle

Currently available cross-flute designs have flute angles of nominally 30° to the direction of airflow (See figure 11 below). CF-1900 & CF-19060 are nominally 31.0° and 30.0° respectively.

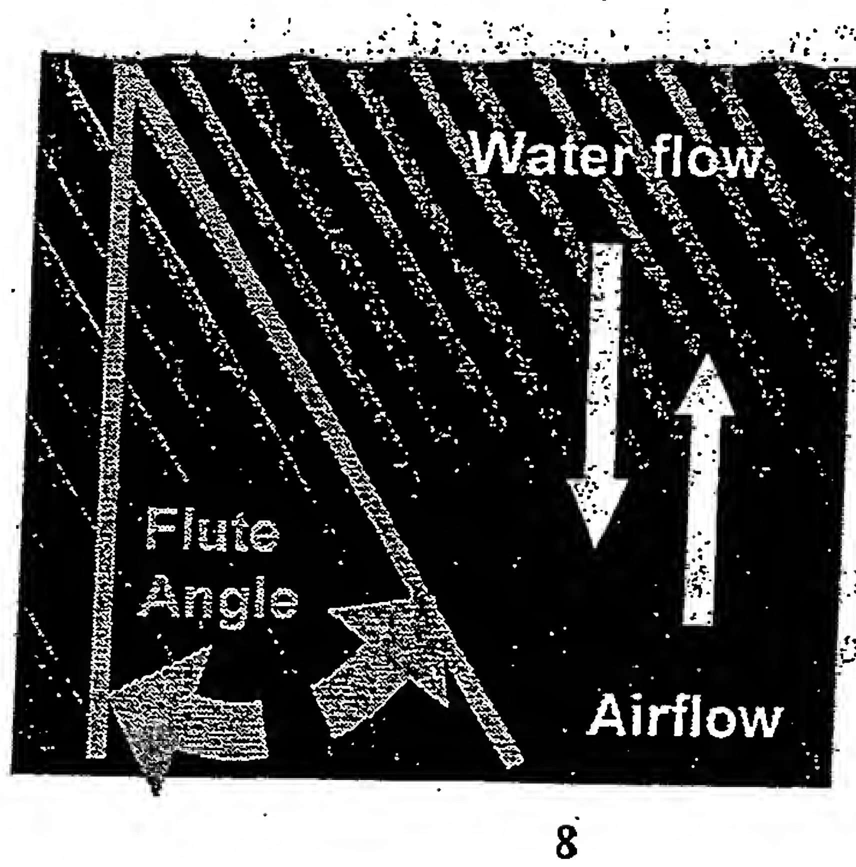

Figure 11.

Packs with 30°, 31° and 34° flute angles were produced and tested. The results are shown in figures 32 through 35. The consequence of the flute angle variation is that the 30° & 34° packs were created without the normal honeycomb arrangement on one side only (See figure 12 below).

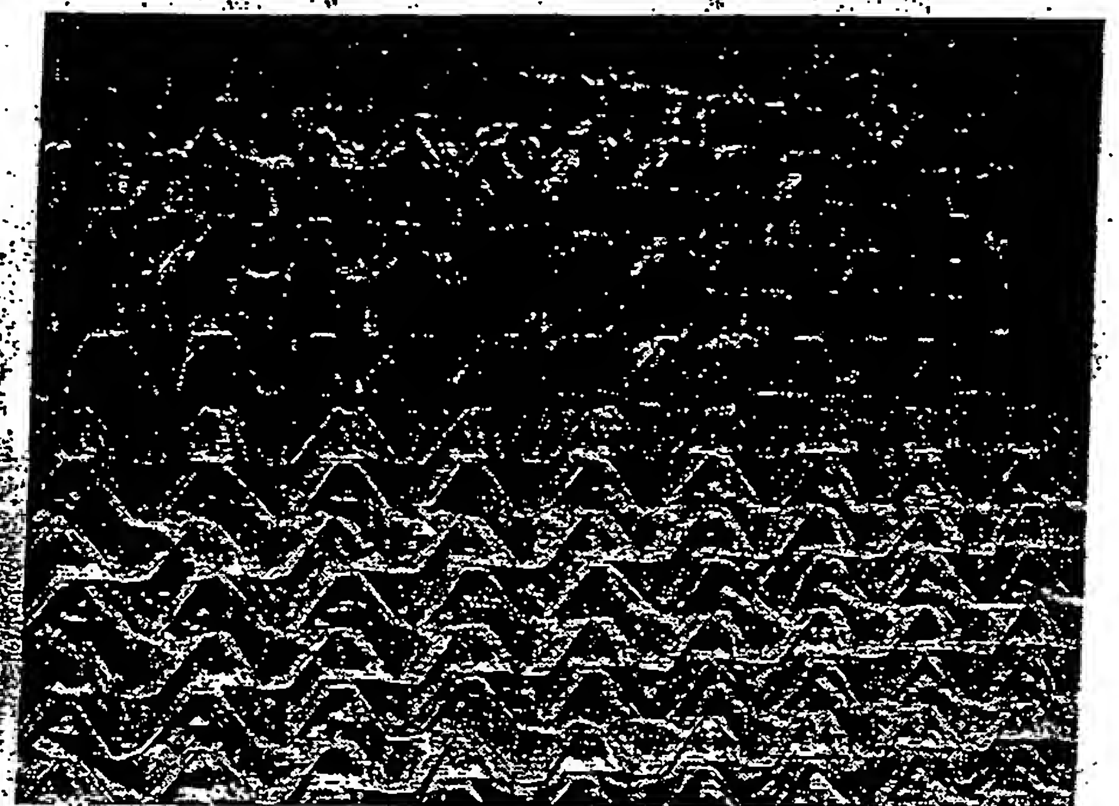

Figure 12. Honeycomb tips (top) & non-honeycomb tips (bottom).

The non-honeycomb surface was installed "up" in the test rig to minimize drainage and tip effects on airside pressure loss. The results of the testing indicate that the 34° flute angle increases the KaV/L value of the packing at the expense of increased pressure loss. The combined affect is to produce a fill with lower overall performance than the current design of 31°. The 30° flute angle pack had a virtually identical characteristic curve to the 31° flute angle pack but the pressure loss was slightly higher. This unexpected result may be caused by the non-honeycomb design, which when coupled with the honeycombed surface of the adjacent layer creates higher interpack transition losses. In any case the results indicate that the optimum angle in the range of 30° to 34° is closer to the typical 30° to 31°.

Alternate Tips

Natural cohesive forces inhibit water from draining efficiently from dense, cross-fluted film fills, especially at higher water loadings. For fills of narrow pitch (i.e. 12mm or less) or with non-honeycomb edges this can cause bridging, an effect that closes off entire flutes to air raising pack pressure loss exponentially. Alternate tips prevent this by extending the distance between sheets at the pack bottom.

19mm & 12mm packs with and without alternate tips were tested and the pressure drop measured dry and at three discreet water loadings. The results are presented in figures 36 through 39. It can be seen that the inclusion of tips in 19mm packs are of some value lowering fill pressure drop by 20% or more, but the flutes are open enough at these water loadings to prevent bridging of the water film. At water loadings higher than 12 gpm/ft^2 the benefit of alternate tips for 19-mm fills would be more pronounced. The benefit of alternate tips are very apparent for 12mm fills. The pressure loss at the high velocity region for no tip (NT) designs are more than double that of the alternate tip (AT) design. It is interesting to note the dry lines for NT vs. AT are similar which indicates the pressure loss is solely due to the influence of the draining water film.

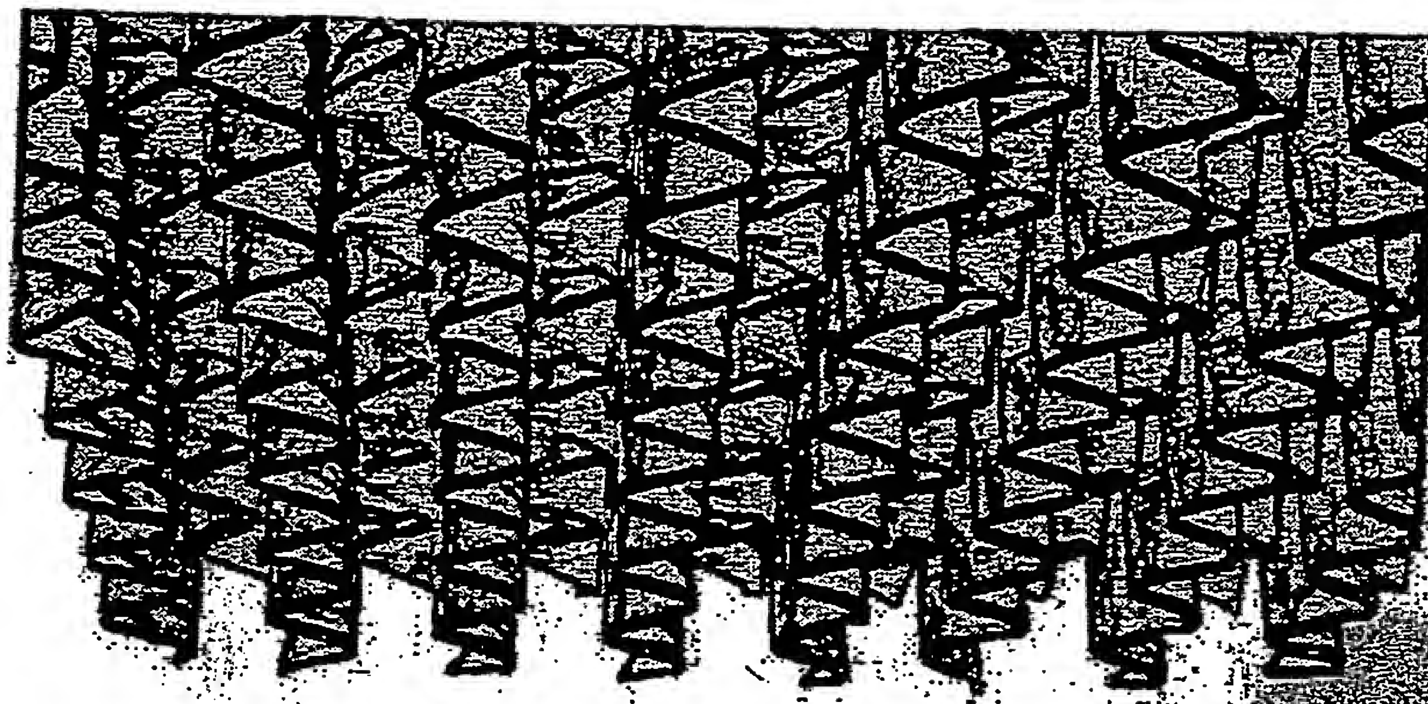

Figure 13. Alternate tip detail

Module Depth

Cross-fluted fills are highly efficient because of their ability to move water laterally during the water films downward flow. Alternating the fill at each layer capitalizes on this feature allowing complete fill surface wetting in as little as two layers, even under poor distribution conditions. However, there is an economic advantage in designing a fill section with packs of deeper dimension. Installation productivity is increased and the initial product cost can be reduced. But, there is a performance penalty.

The performance of 2' and 1' modules in a 48" deep fill section were tested with results presented in figures 40 through 43. The pressure losses of both configurations are virtually identical, but the KaV/L values differ at the low L/G values, showing the dependence on water loading. Since PVC (and all plastic materials) are hydrophobic (resist wetting), the effect of the poor surface utilization is more pronounced at the low water loadings (incomplete wetting). At higher water loadings the effect is almost non-existent (at 8 gpm/ft^2 the difference between the configurations is 1.5%). It must be emphasized that this effect will be amplified if the water distribution system is compromised in some way, but deeper fill sections will help mitigate this trend.

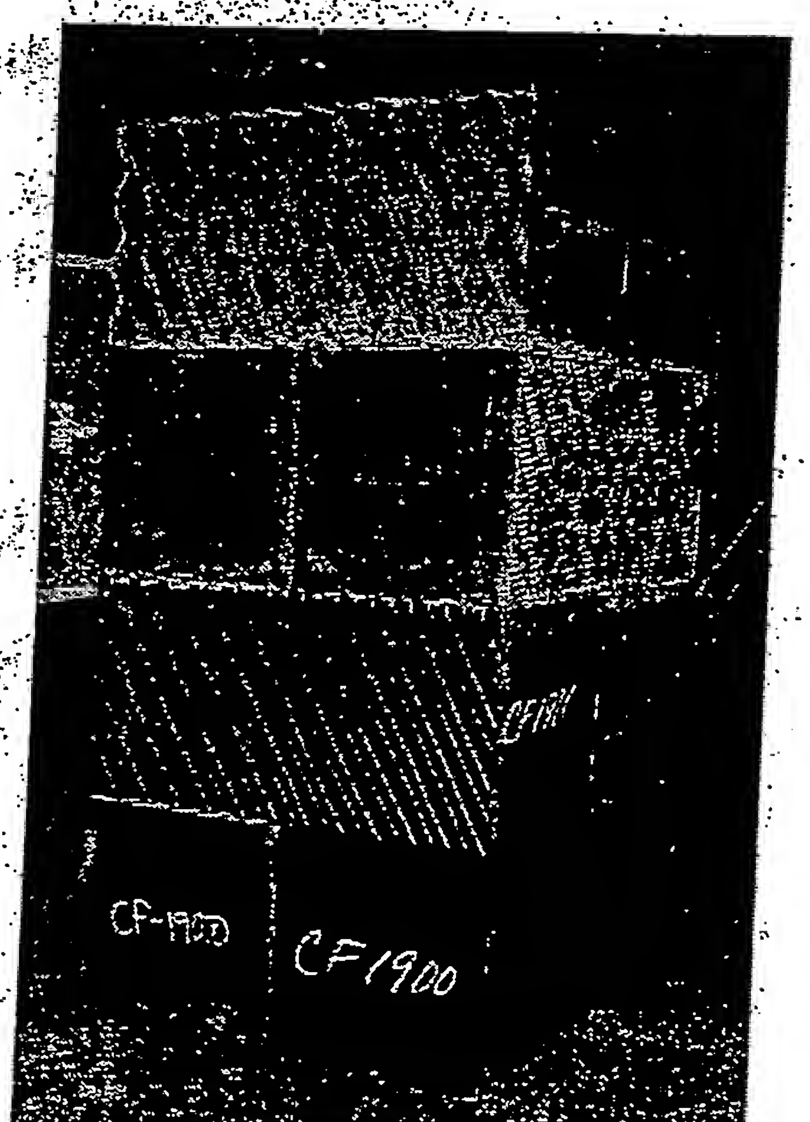

Figure 14. 1' (300mm) module depth

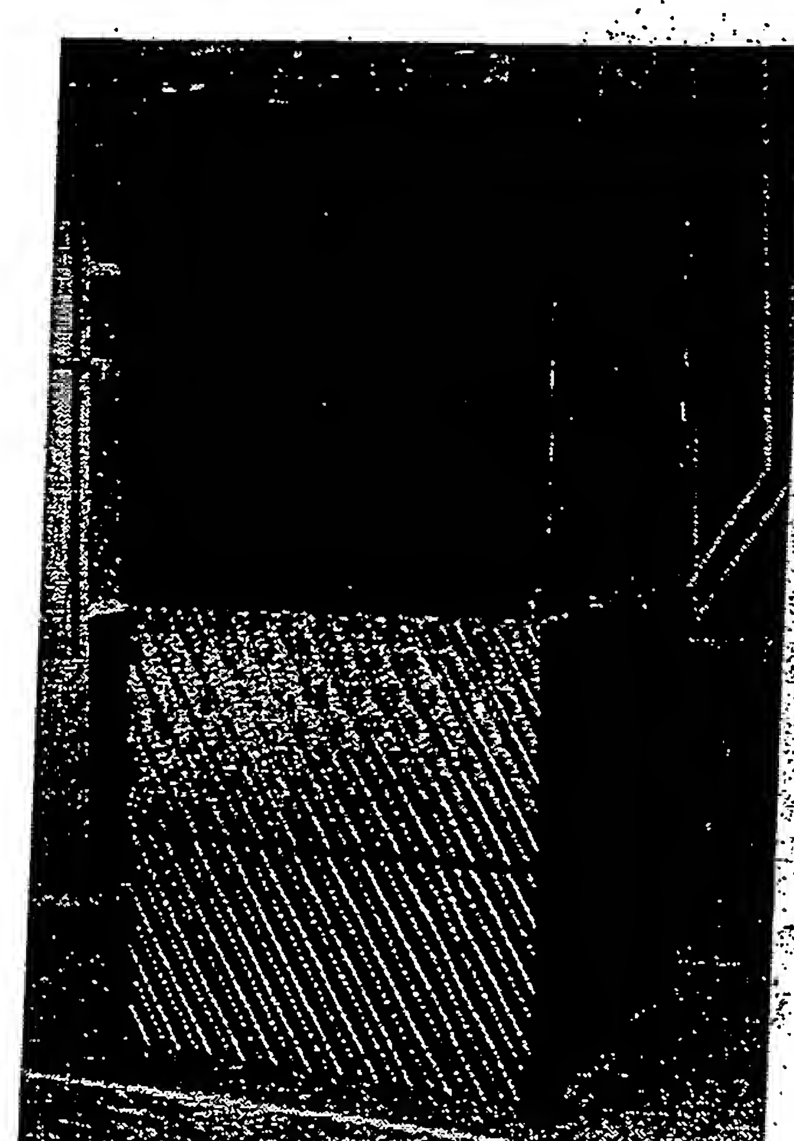

Figure 15. 2' (600mm) module depth

Materials of Construction & Affect of Aging

PVC is the workhorse material of film fill, with its high strength, resistance to harsh chemicals and flame retardency its greatest virtues. With special compounding PVC can be formulated to withstand continuous operating temperatures of up to 150°F (65°C).

Polypropylene (PP) is another viable polymer for use in film fill, since its processability is good and its temperature resistance can reach to 180°F (82°C) . Unfortunately, it has two serious drawbacks: flammability and poor wetting characteristics. Fire resistance can be increased through the use of additives. Wetting can be improved only with age (time spent in service). Fire resistance can be improved by the addition of antimony salts, which can have negative environmental consequences. Wetting can be improved with time, but at low water rates it may never reach its full potential.

As stated earlier, the natural surface of any polymer is by nature hydrophobic, that is water tends to bead-up and resists forming a smooth and uniform water film. With inadequate water film development, the expected performance of the fill will not be achieved and performance will suffer. While in service, the fill's surface becomes less hydrophobic and over time the surface becomes fully conditioned (aged) allowing water to form a thin film. In out tests aging was accelerated by introducing a concentrated detergent solution (trisodium phosphate) into the circulating water. We estimate that one week in the aging facility is equivalent to about four weeks of use in an actual cooling tower.

Newly manufactured packs and packs aged one, two and three weeks were tested and performance determined. The most striking evidence of a poorly aged pack is the staggered arrangement of the characteristic curve as a function of waterloading (figure 44). The lack of a conditioned surface and poor wetting is amplified at low waterloadings (especially at less than 5 4 gpm/ft^2). These water loadings are typical for natural draft towers and for towers designed for high energy evaluations (low approach). At higher waterloadings where the water film is thicker, the affect of aging is less pronounced.

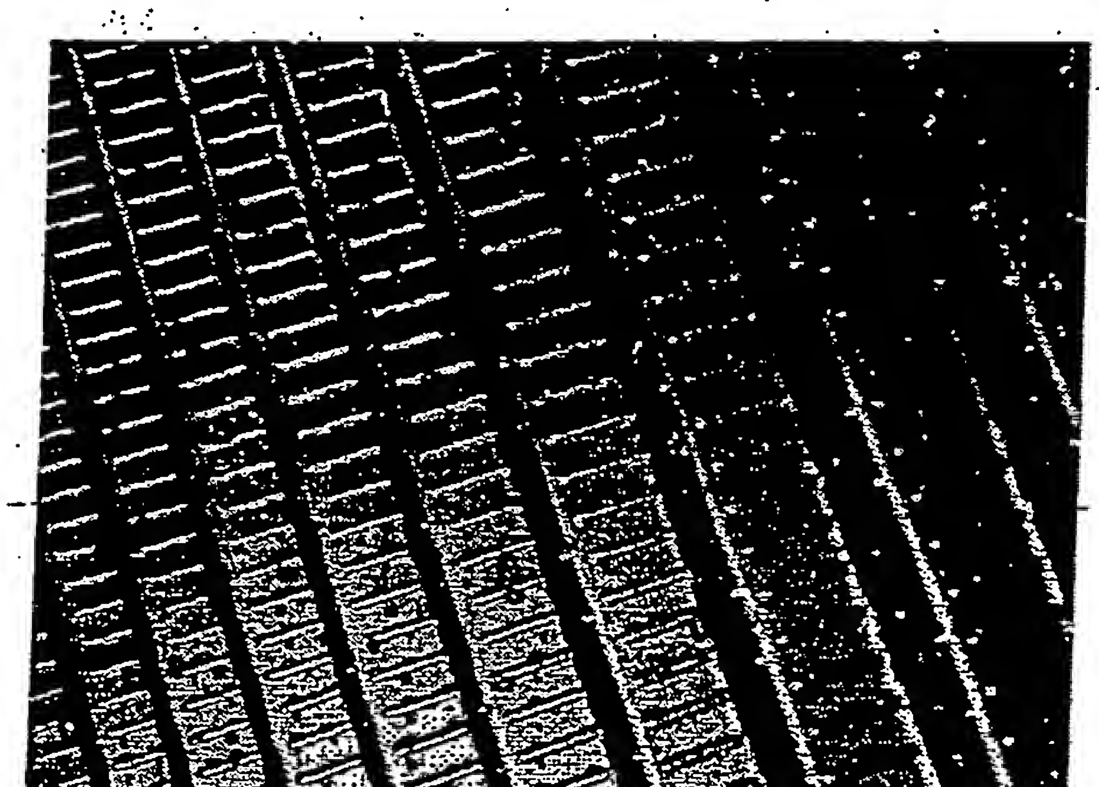

Figure 16. Un-aged PVC fill surface. Note water droplets on surface. At low water loadings, incomplete wetting occurs lowering fill performance.

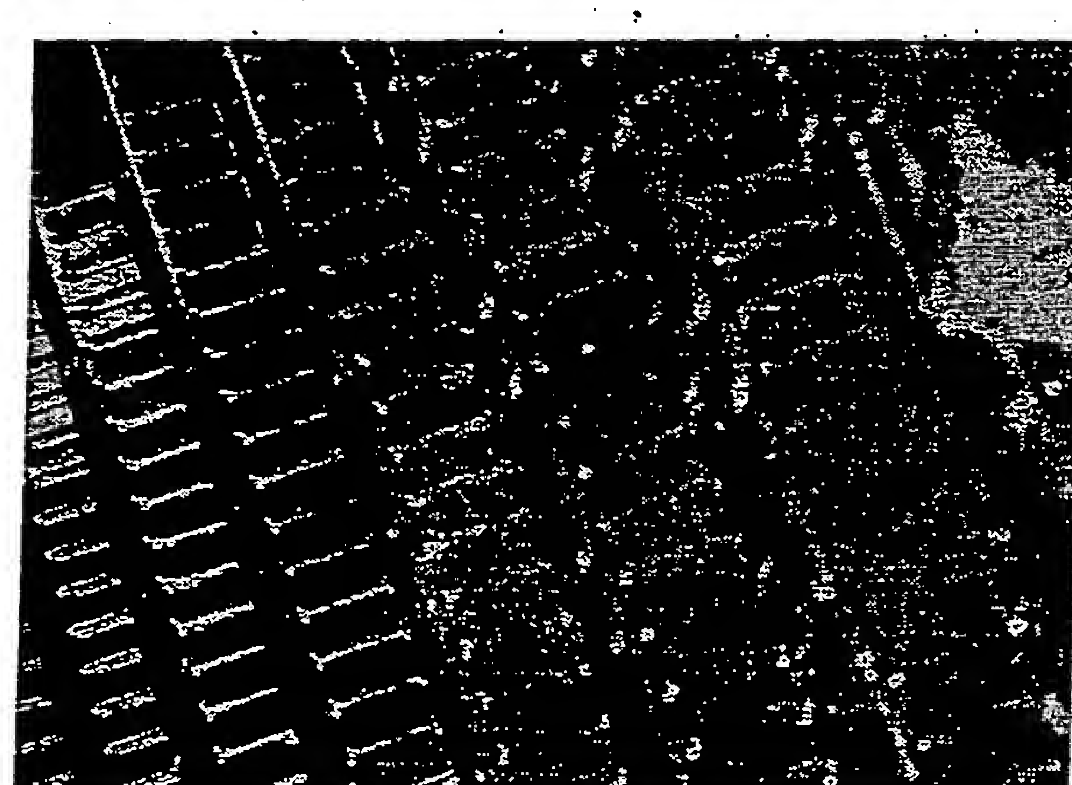

Figure 17. Fully aged PVC fill surface. Water is spread uniformly on surface, achieving 100% surface utilization.

Figure 45 shows the same packs after one week of conditioning. The characteristic curves have all pulled together showing nearly complete wetting. The results indicate the obvious necessity of a fully aged fill section before certification and/or performance tests are conducted. This is especially so when low approach towers are designed with the commensurate low waterloadings.

Polypropylene has a more "waxy" surface and is very difficult to age. After three weeks in the aging facility the low waterloading characteristic curve is still not fully developed (compare figures 50 & 51). The low waterloading curve of the three week-aged fill hasn't reached full wetting & requires further conditioning as evidenced by the 3.5 gpm/ft^2 curve not fully lining up with the 6 & 8 gpm/ft^2 curves. The conclusion is that polypropylene fills will not achieve their full performance potential for 2-3 times that of PVC (this could translate 2-3 months in service) and may never at the lower water rates. Towers with polypropylene fills with low waterloadings cannot be expected to perform to their design levels for periods of 3 months or more after initial operation.

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Appendix 1

Brentwood Industries Twin Test Cell

Brentwood's twin test cell allows fill evaluations to be performed side-by-side, in real time. The test sections are made of clear high-strength polycarbonate material that allows direct observation of the fill under test, the spray pattern of the nozzle and the interaction of the air & water.

Figure 18. Twin test cell.

Air-side:

Air is provided by two centrifugal fans (one per cell) that can sustain a 1000-fpm (5 m/s) velocity against a static pressure of 2-in. wg. (51mm wg.) Fan speed can be varied with infinite control by variable frequency drives.

Air velocity is measured by a multi-port, averaging pitot tube in a venturi section of the air intake (one per cell). The pitot tube differential pressure is sensed by draft-range pressure transducers located remotely on the control panel. Inlet and exit air wet & dry bulb temperatures are measured with precision platinum, 3-wire RTD's calibrated to mercury-in-glass thermometers whose calibrations are traceable to NIST.
Fill pressure-drop is measured using paired, static 'H' taps, one at the spray nozzle elevation above the fill and one directly below the fill in each cell. Output is sent via tubing to precision, draft-range pressure transducers.

Water-side:

Water is circulated by a centrifugal pump capable of supplying each cell with 40 gpm ($9m^3/hr$). The pump is controlled by a variable frequency drive, which allows a continuously adjustable flow rate to provide fill specific waterloadings of 2 gpm/ft^2 to 12 gpm/ft^2 ($5m^3/hr\text{-}m^2$ to 30 $m^3/hr\text{-}m^2$).

Waterflow is measured by two calibrated magnetic flow meters in the hot water lines.

A 1.2 million BTU/hr (350 kW) hot-water generator supplies the heat load. Water is circulated through a heat exchanger to isolate the heater water from the cooling tower water. Hot water

temperature is maintained at a constant value during testing with a microprocessor-based PID controller that operates a three-way mixing valve.

Water is delivered to the fill by specially designed nozzles to provide a full solid cone, square spray pattern at 9" (230mm) above the fill.

<u>Fill Test Section:</u>

The tower can accommodate up to 5 ft (1525mm) of fill. The spray nozzle is attached to a motorized trolley that allows for accurate focus of the nozzle spray, or for custom spray arrangements, while the tower is in operation.

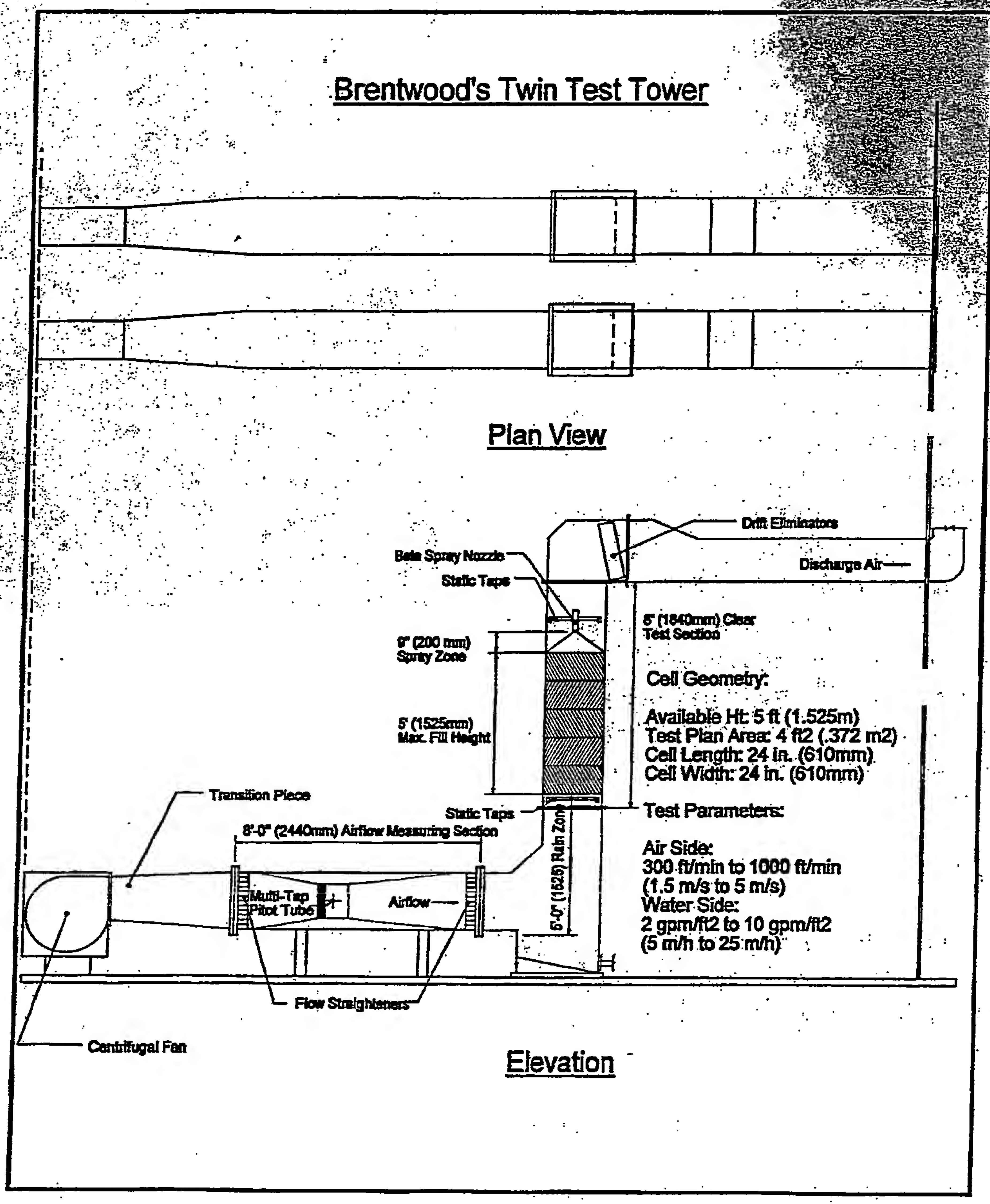

Figure 19. Sketch of test cell showing principal dimensions.

Appendix 2

Sample Air-Horsepower Calculation
Comparison of 1' modules vs. 2' modules

Characteristic curve equation for 1' module of CF-1900 (4' fill height total):

$$KaV/L = 2.055(L/G)^{-0.736}$$

Characteristic curve equation for 2' modules of CF-1900 (4' fill height total):

$$KaV/L = 1.840(L/G)^{-0.628}$$

Using the CTI BlueBook Software for the condition of 104/84/78 (hot water temperature/cold water temperature/wet bulb temperature) yields a design L/G of 1.016 for the 1' modules and an L/G of 0.937 for the 2' modules (see BlueBook Demand Curve sheets below).

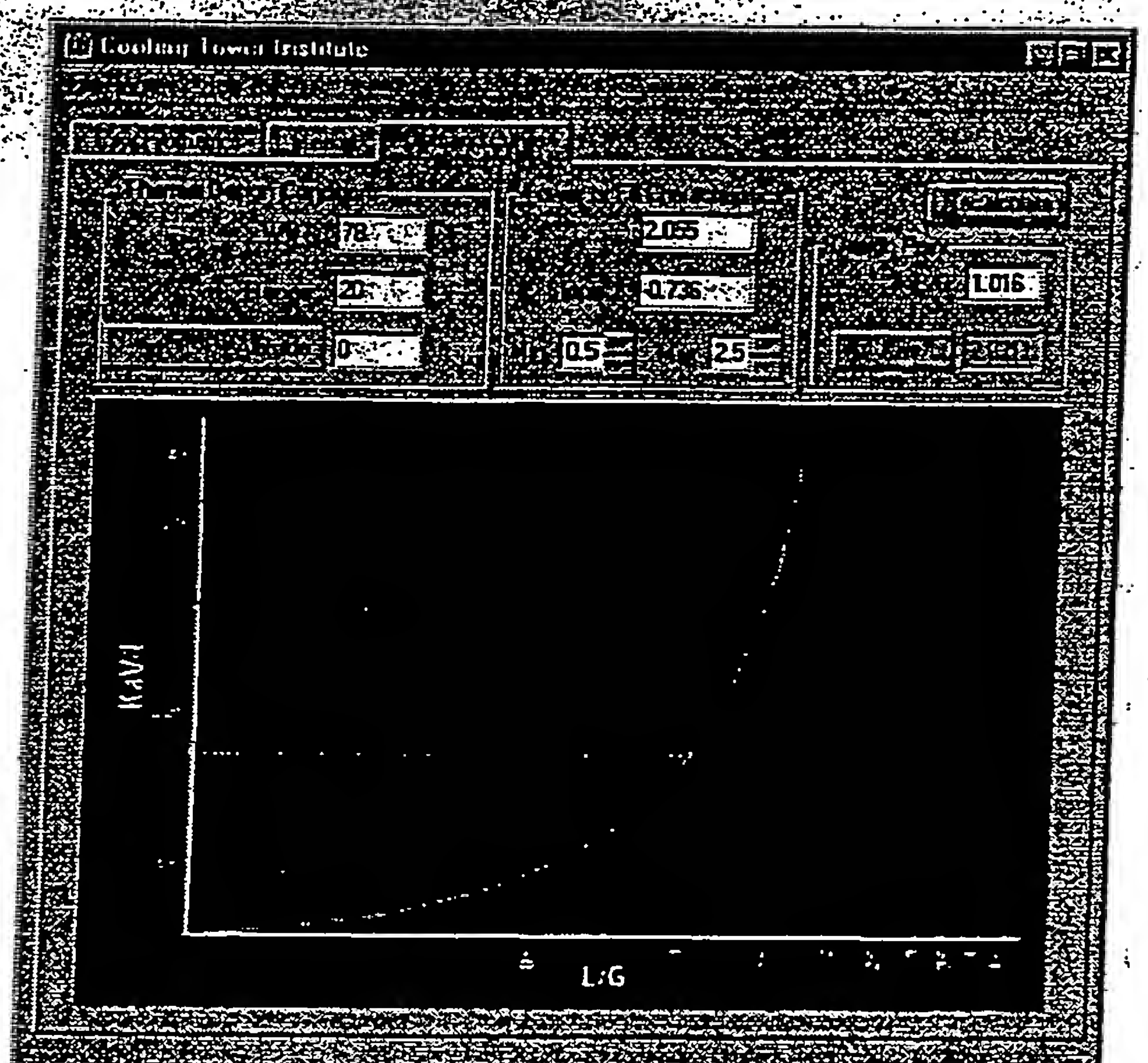

Figure 20. 1' module L/G calculation.

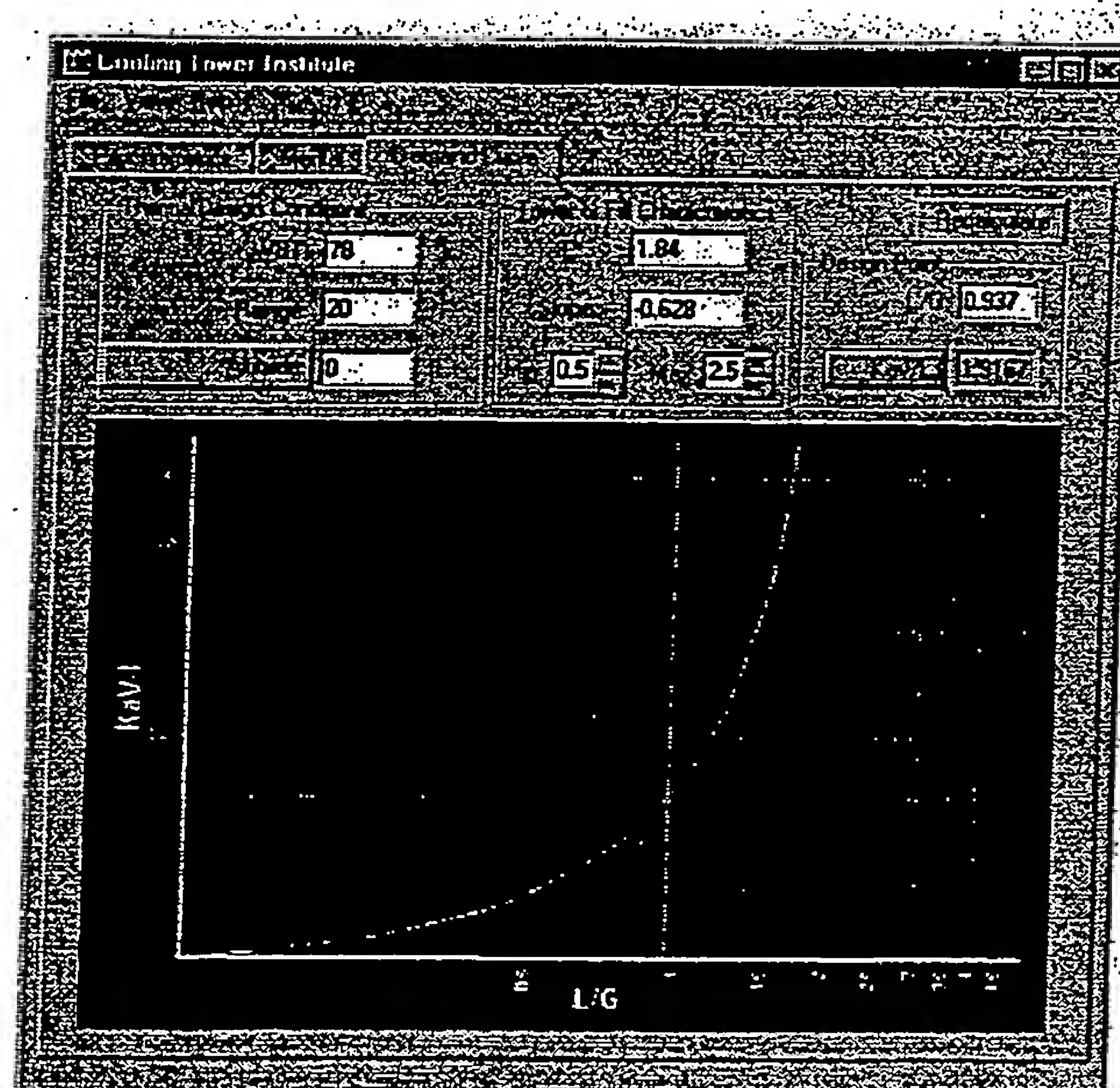

Figure 21. 2' module L/G calculation.

The calculation is based on $1ft^2$ of tower plan area. At 3.5 gpm/ft^2 we have 3.5 gal/min flowing into this "tower". Knowing "L" we can calculate "G" since G= L/(L/G). "L" is mass/unit time and in English units equals 3.5 gal/min x 8.28 lb/gal or 28.98 lb/min. Thus G = 28.98/1.016 = 28.52 lb dry air/min. Calculating the exit air temperature using the exact heat balance yields 94.6°F. Knowing the inlet and outlet air temperatures, we can calculate the average specific volume of the air as it passes through the fill and then the average air velocity.

Using the Psychrometrics tab of the BlueBook software to calculate specific volume we get:

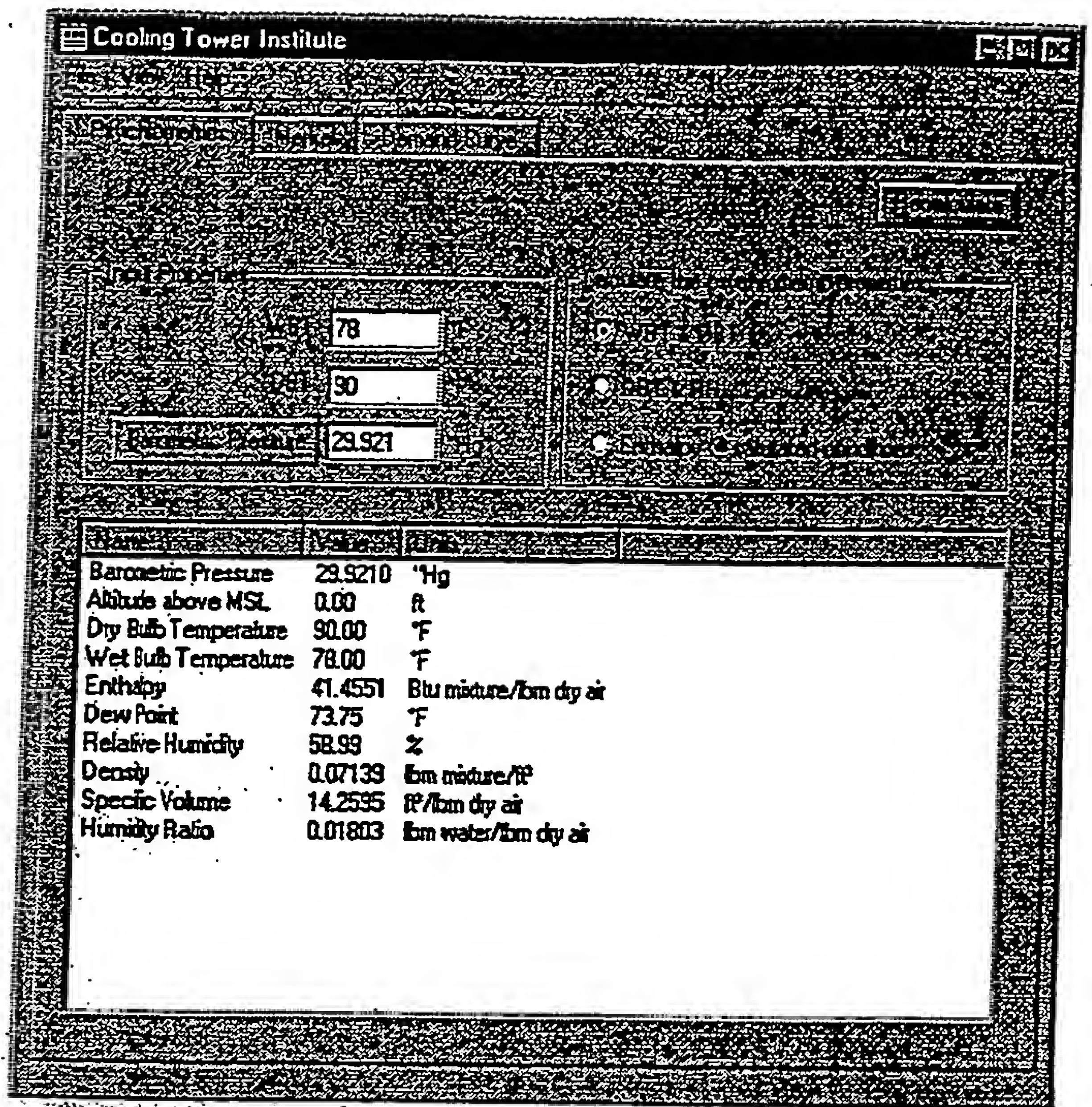

Figure 22. Inlet conditions: 14.2595 ft^3/lb dry air.

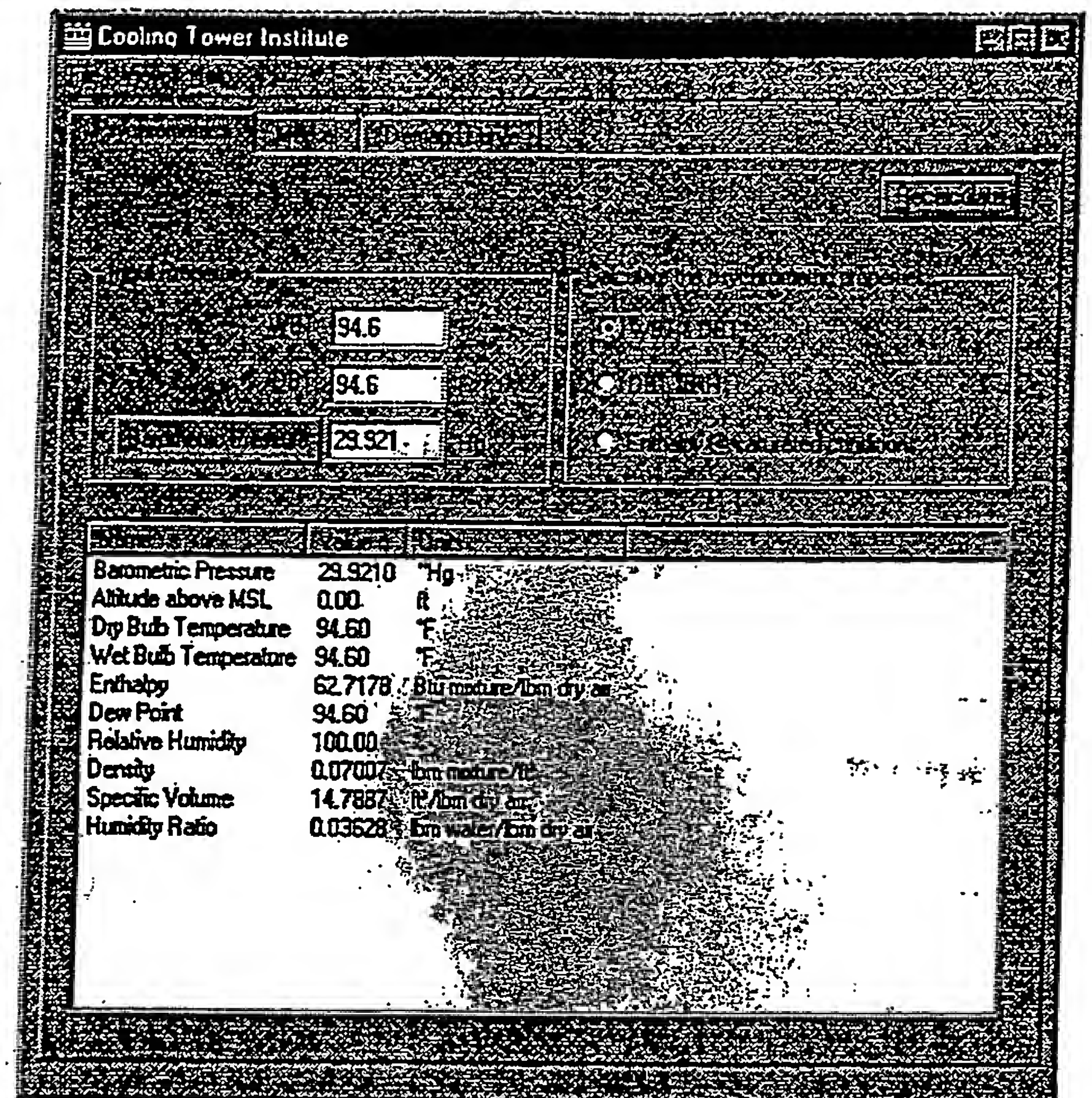

Figure 23. Exit conditions we get: 14.7887 ft^3/lb dry air.

Averaging the specific volume to calculate the average air velocity through the fill (needed for pressure drop calculation):

$$= (14.2595+14.7887)/2 = 14.5241 \text{ ft}^3/\text{lb dry air}$$

Average air velocity $= \text{lb/min dry air} \times \text{average specific volume}$

$$= 28.52 \times 14.5241 = 414 \text{ ft/min}$$

Fill pressure drop at 414 ft/min is 0.206 in. wg.

Air horsepower is to be calculated at the exit air volume:

$$= 414 \text{ ft/min} \times 14.7887 \text{ ft}^3/\text{lb}/14.5241 \text{ ft}^3/\text{lb} = 421.5 \text{ ft/min}$$

Air horsepower per 1000 ft^2 of tower plan area (using equation 2.32 from ref. 5):

$$= 421.5 \text{ ft/min} \times 0.206 \text{ in.wg.}/6356 \times 1000\text{ft}^2 = 13.7 \text{ air hp}/1000\text{ft}^2$$

Similarly we calculate the air horsepower of the 2' modules:

Air horsepower per 1000 ft^2 of tower plan area:

$$= 455.4 \text{ ft/min} \times 0.233 \text{ in. wg.}/6356 \times 1000\text{ft}^2 = 16.7 \text{ air hp}/1000\text{ft}^2$$

Capability = cube root of the ratio of the fan hp:

$$= (13.7/16.7)^{1/3} = 93.6\%$$

This calculation was carried out for all 3.5, 6 and 8 gpm/ft^2 for all fills investigated in a like manner. The 6 & 8 gpm/ft^2 cases were calculated at 108/88/78 and 112/92/78, respectively.

Appendix 3 - Figures

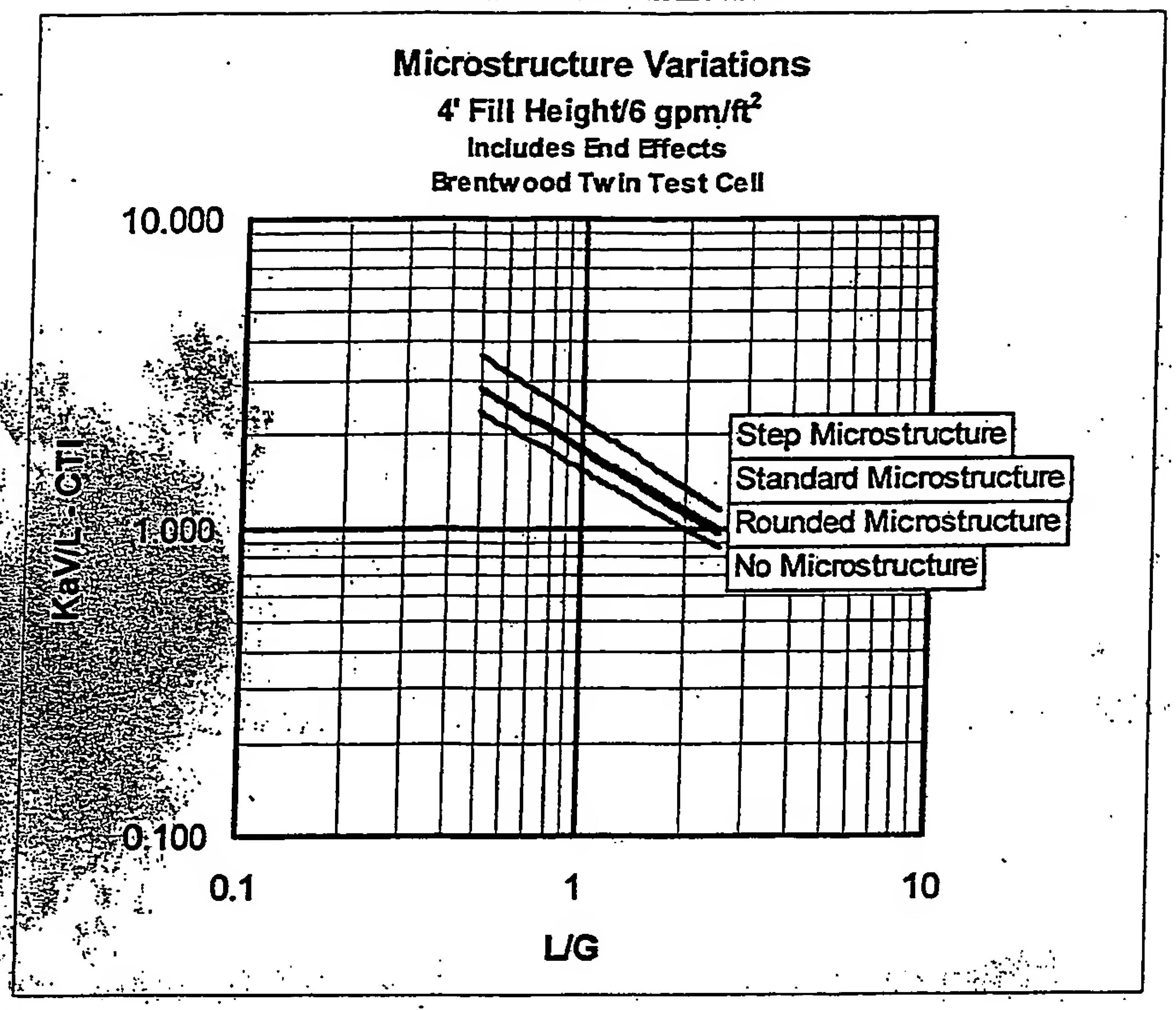

Figure 24.

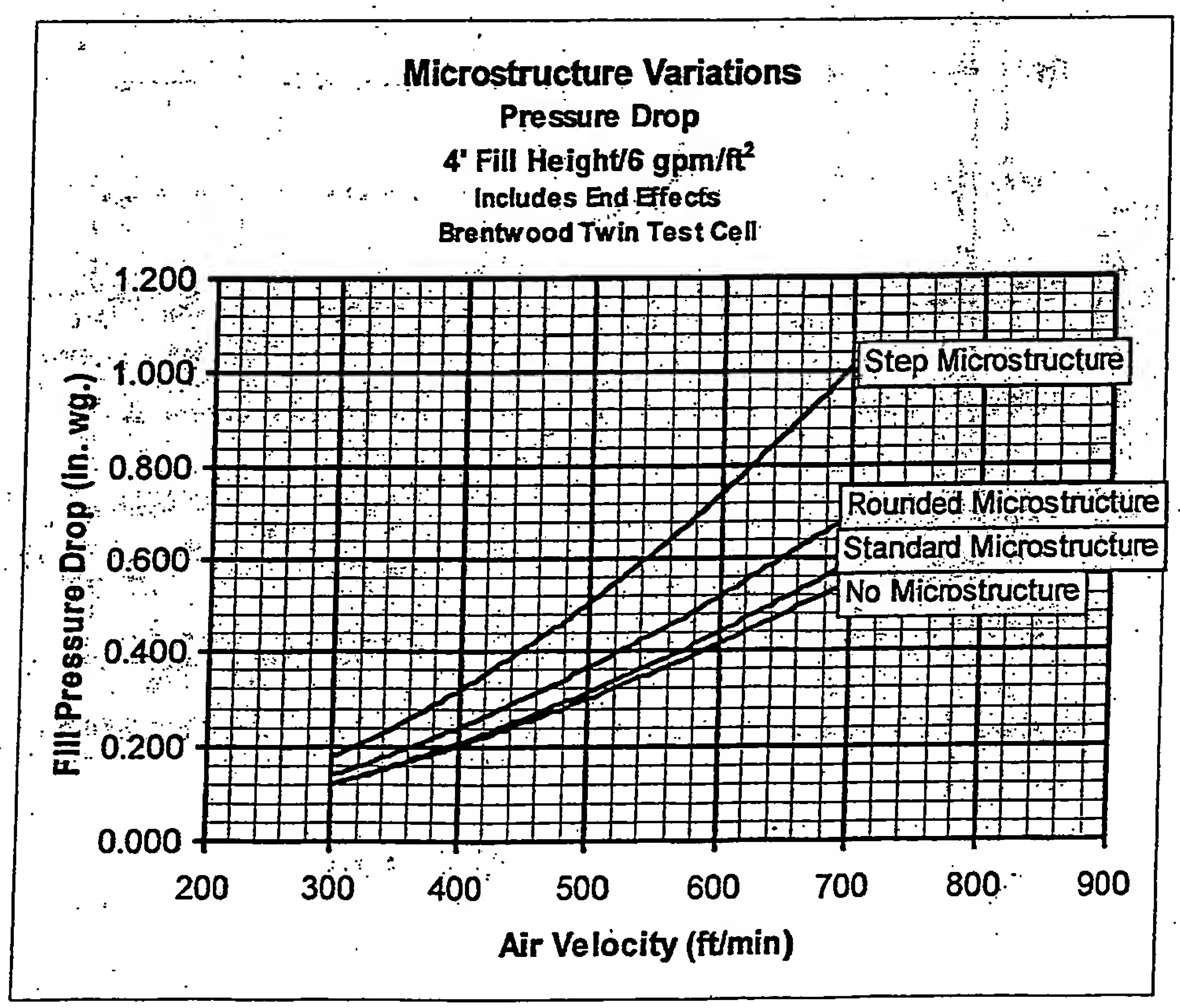

Figure 25.

Microstructure Type	q/a (gpm/ft^2)	l/g	fill vel (ft/min)	fill dp (in. wg.)	hp/1000ft^2	Capability (%)
None	3.5	0.807	518.6	0.280	23.1	Base
Step	3.5	1.065	395.5	0.271	17.2	10.4%
Rounded	3.5	0.925	453.8	0.266	19.3	6.3%
Standard	3.5	0.911	460.6	0.234	17.2	10.4%
None	6	1.217	595.0	0.393	37.6	Base
Step	6	1.510	482.8	0.440	34.4	3.0%
Rounded	6	1.358	535.0	0.396	34.2	3.2%
Standard	6	1.333	544.7	0.350	30.8	6.9%
None	8	1.665	585.4	0.407	38.7	Base
Step	8	1.983	495.1	0.491	39.8	-0.9%
Rounded	8	1.824	536.3	0.422	36.9	1.6%
Standard	8	1.789	546.4	0.375	33.4	5.1%

Figure 26.

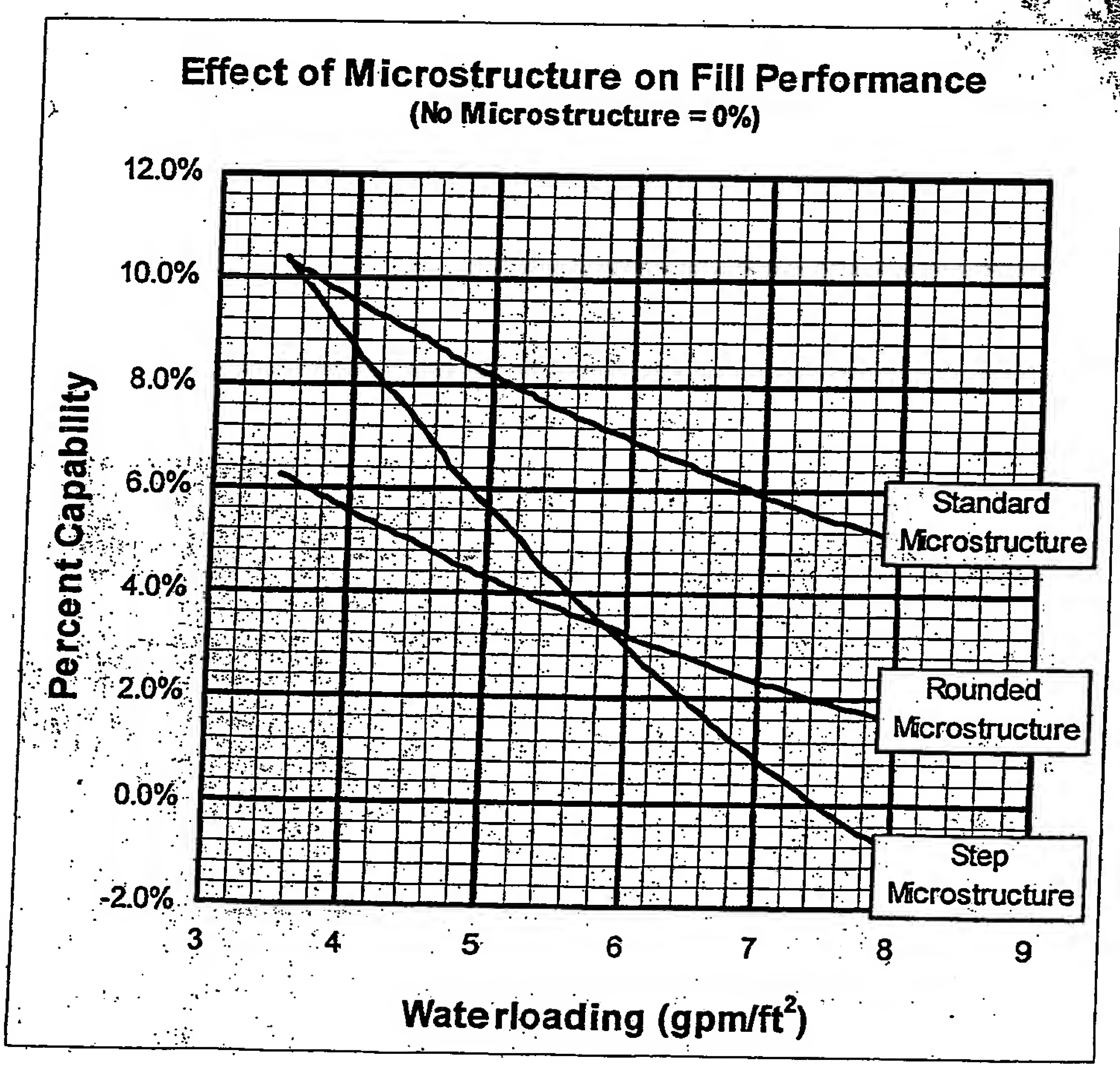

Figure 27.

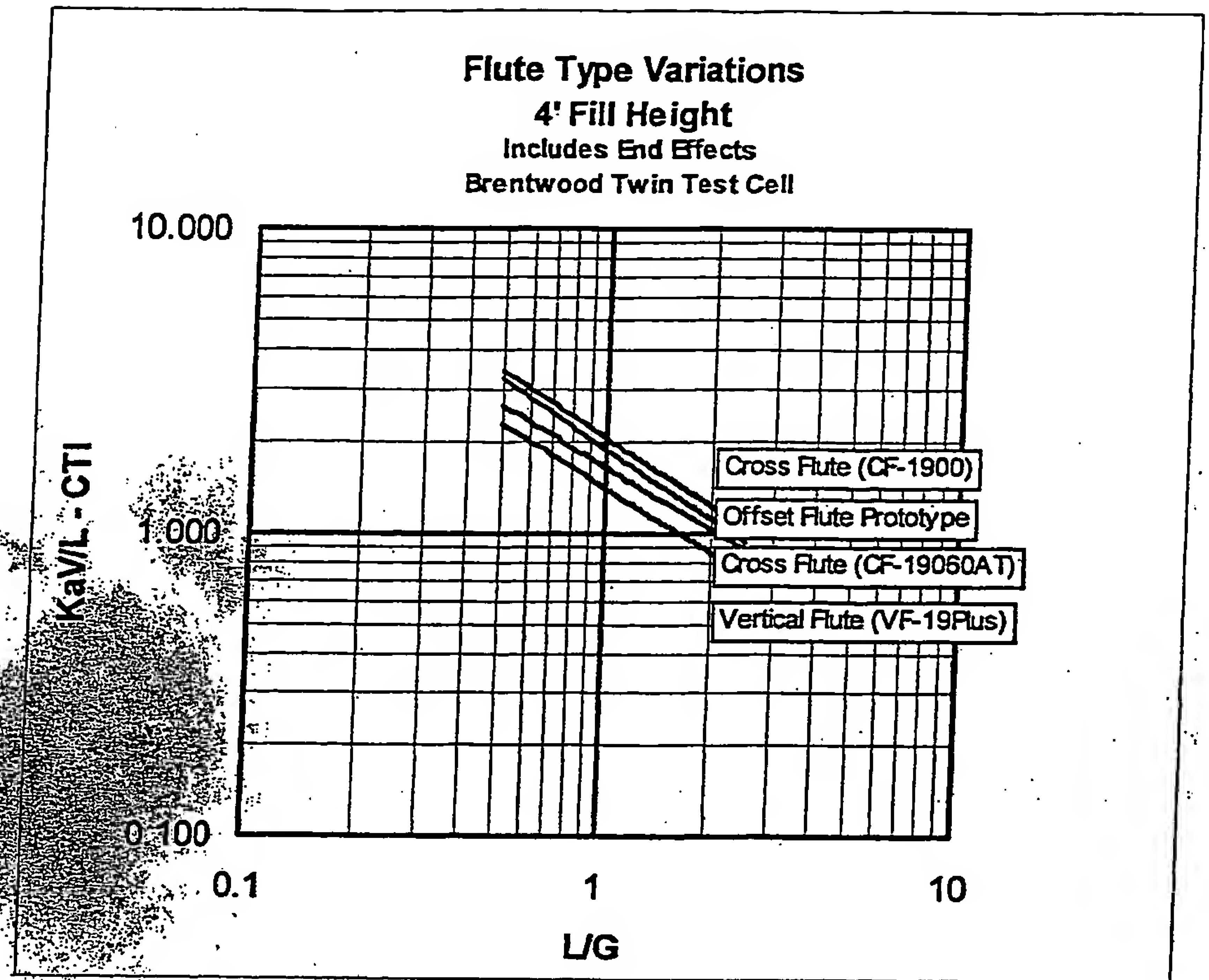

Figure 28.

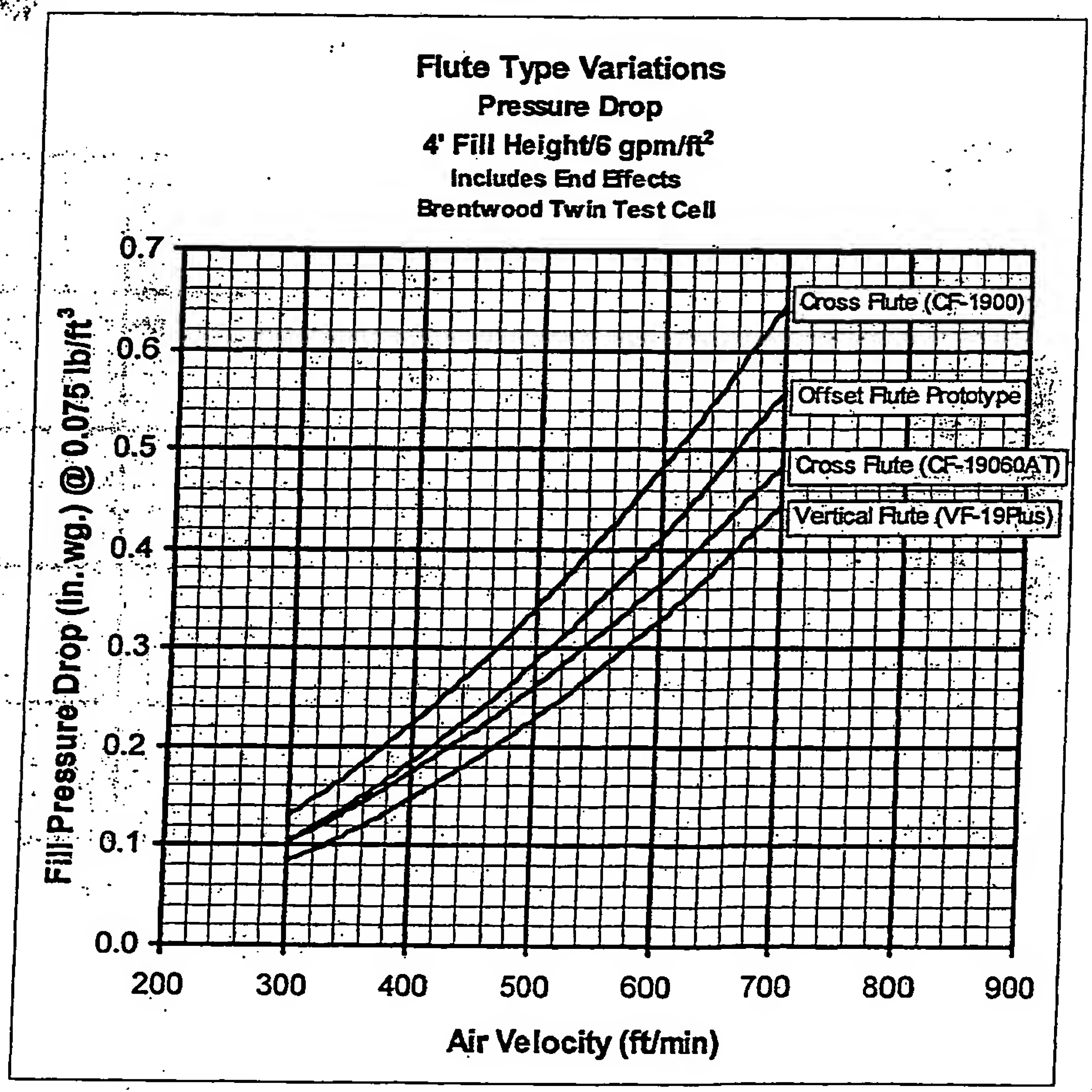

Figure 29.

Flute Type	q/a (gpm/ft^2)	l/g	fill vel (ft/min)	fill dp (in. wg.)	hp/1000ft^2	Capability (%)
Cross Flute (CF-1900)	3.5	1.016	414.0	0.206	13.7	100.0%
Cross Flute (CF-19060AT)	3.5	0.863	485.6	0.211	16.4	94.2%
Offset Flute (Prototype OF)	3.5	0.962	436.7	0.183	12.8	102.2%
Vertical Flute (VF-19Plus)	3.5	0.759	550.7	0.236	20.7	87.1%
Cross Flute (CF-1900)	6	1.445	503.8	0.327	26.7	100.0%
Cross Flute (CF-19060AT)	6	1.272	570.0	0.318	29.2	97.0%
Offset Flute (Prototype OF)	6	1.369	530.8	0.306	26.2	100.5%
Vertical Flute (VF-19Plus)	6	1.127	641.1	0.358	36.9	89.8%
Cross Flute (CF-1900)	8	1.904	514.7	0.365	30.7	100.0%
Cross Flute (CF-19060AT)	8	1.716	568.7	0.343	31.7	98.9%
Offset Flute (Prototype OF)	8	1.806	541.5	0.347	30.6	100.1%
Vertical Flute (VF-19Plus)	8	1.530	635.1	0.381	39.2	92.1%

Figure 30.

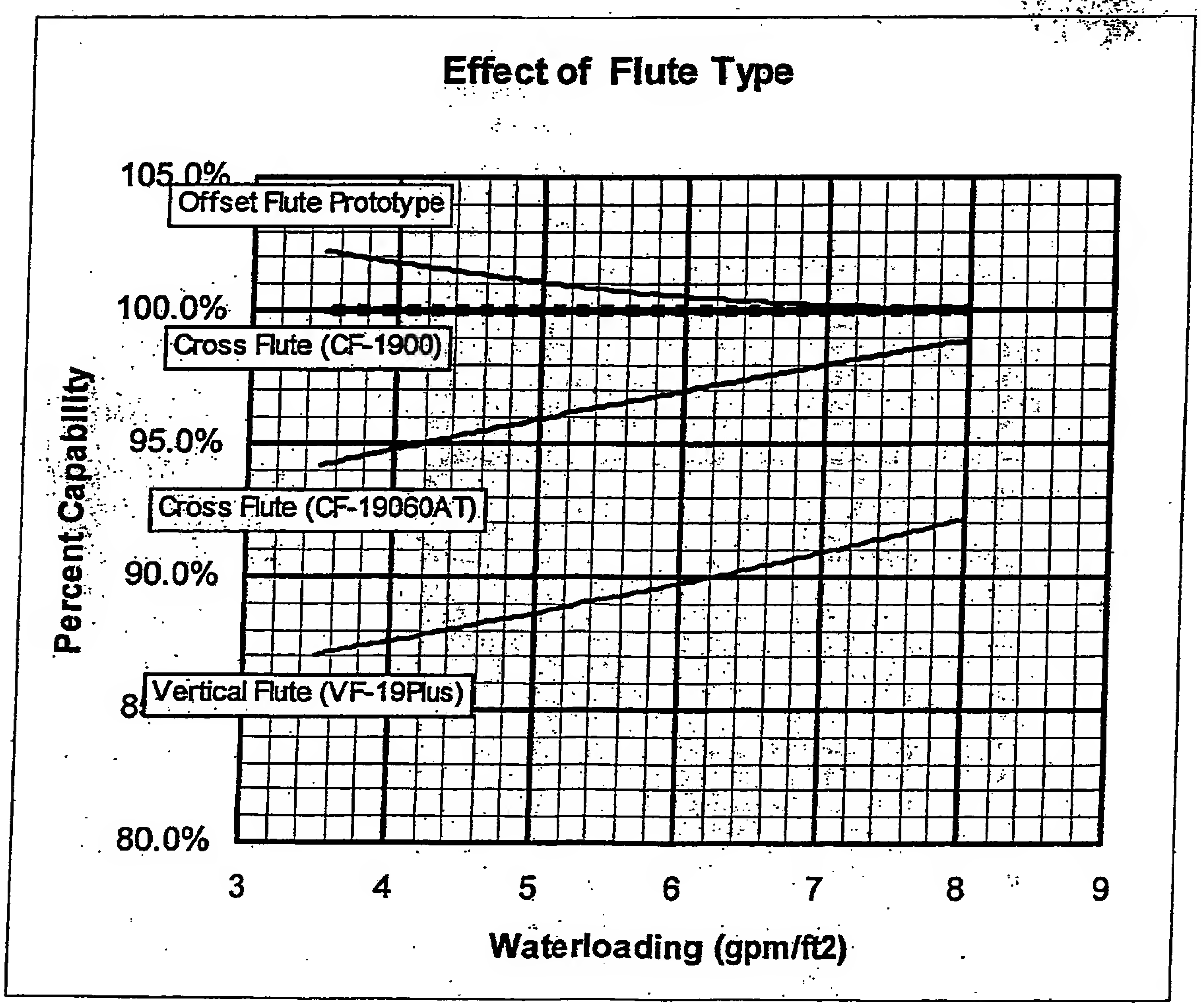

Figure 31.

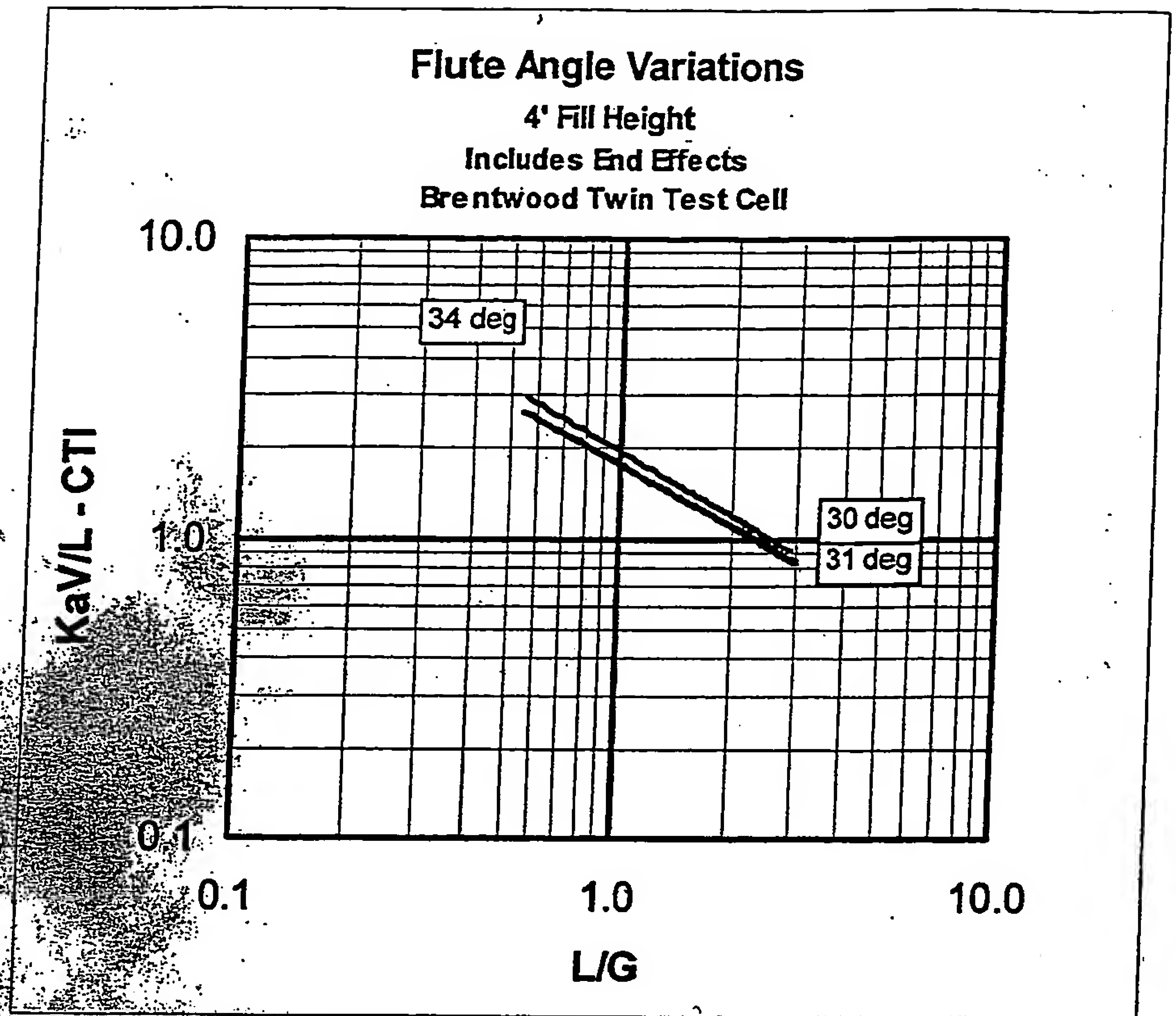

Figure 32.

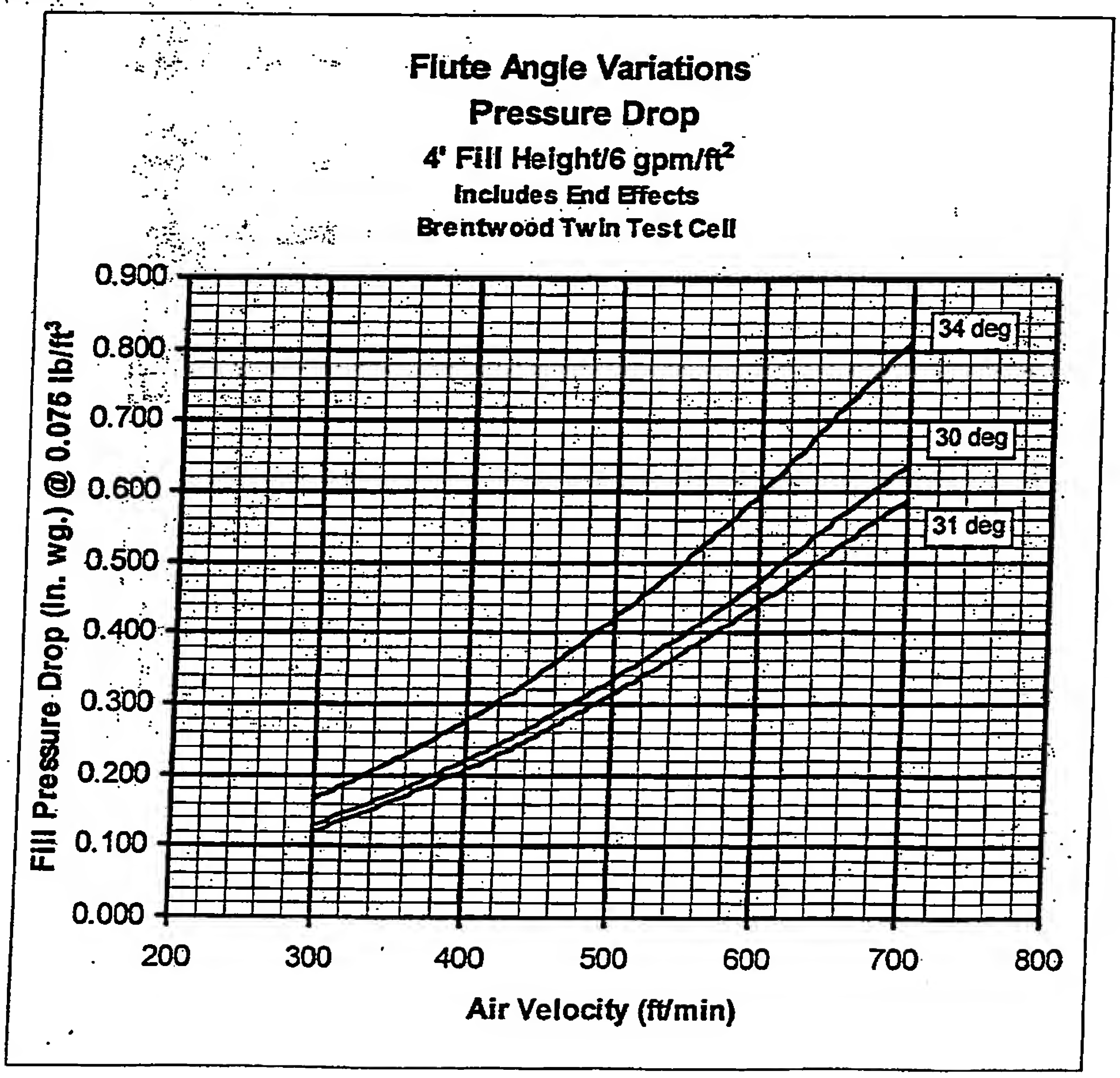

Figure 33.

Flute Angle (deg)	q/a (gpm/ft^2)	l/g	Fill Vel (ft/min)	fill dp (in. wg.)	hp/1000ft^2	Capability (%)
31	3.5	0.911	460.6	0.234	17.2	100.0%
30	3.5	0.906	463.1	0.251	18.6	97.5%
34	3.5	0.980	428.9	0.282	19.4	96.2%
31	6	1.333	544.7	0.350	30.8	100.0%
30	6	1.324	548.2	0.379	33.5	97.2%
34	6	1.406	517.3	0.426	35.6	95.2%
31	8	1.789	546.4	0.375	33.4	100.0%
30	8	1.775	550.5	0.409	36.7	96.9%
34	8	1.863	525.5	0.462	39.6	94.5%

Figure 34.

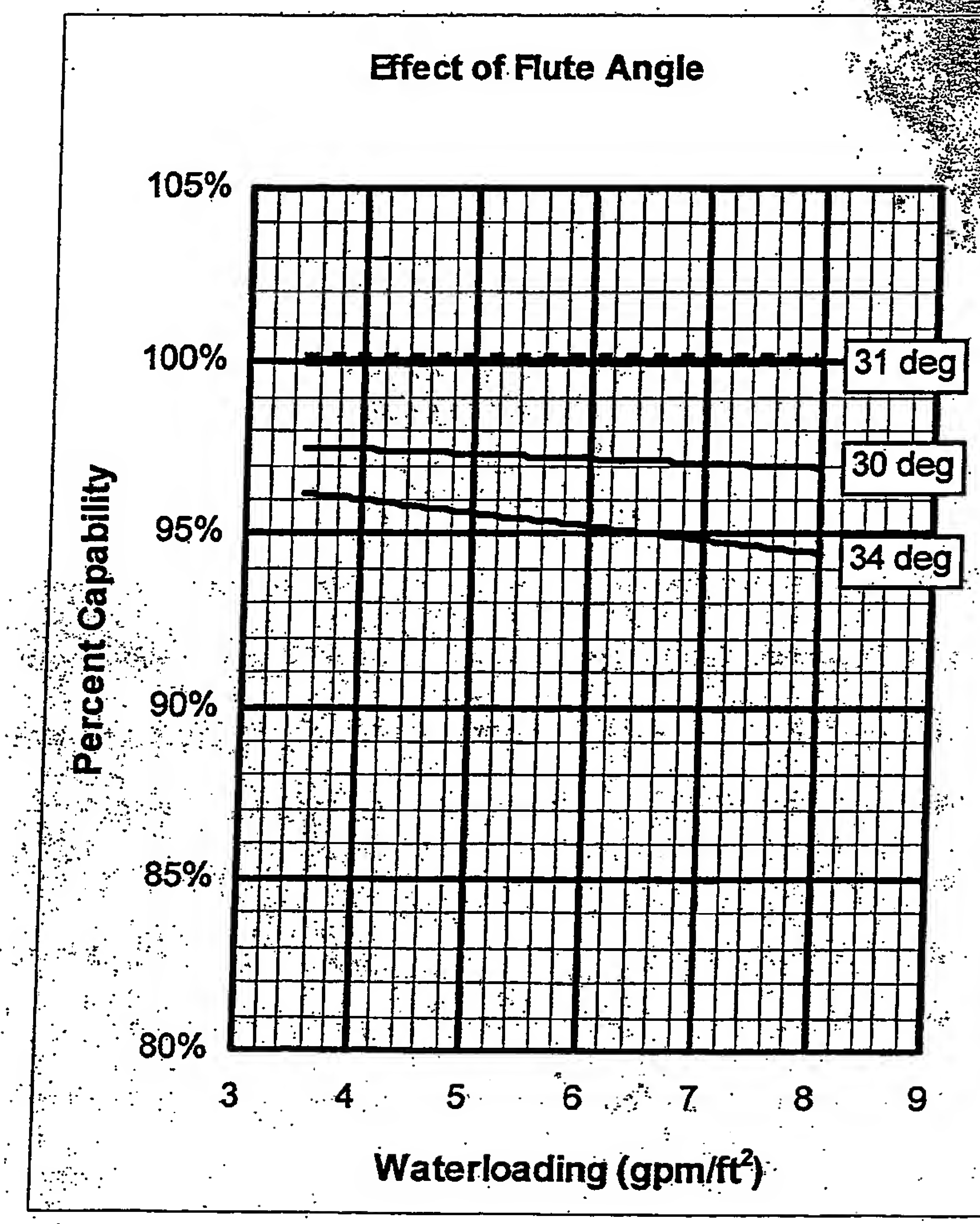

Figure 35.

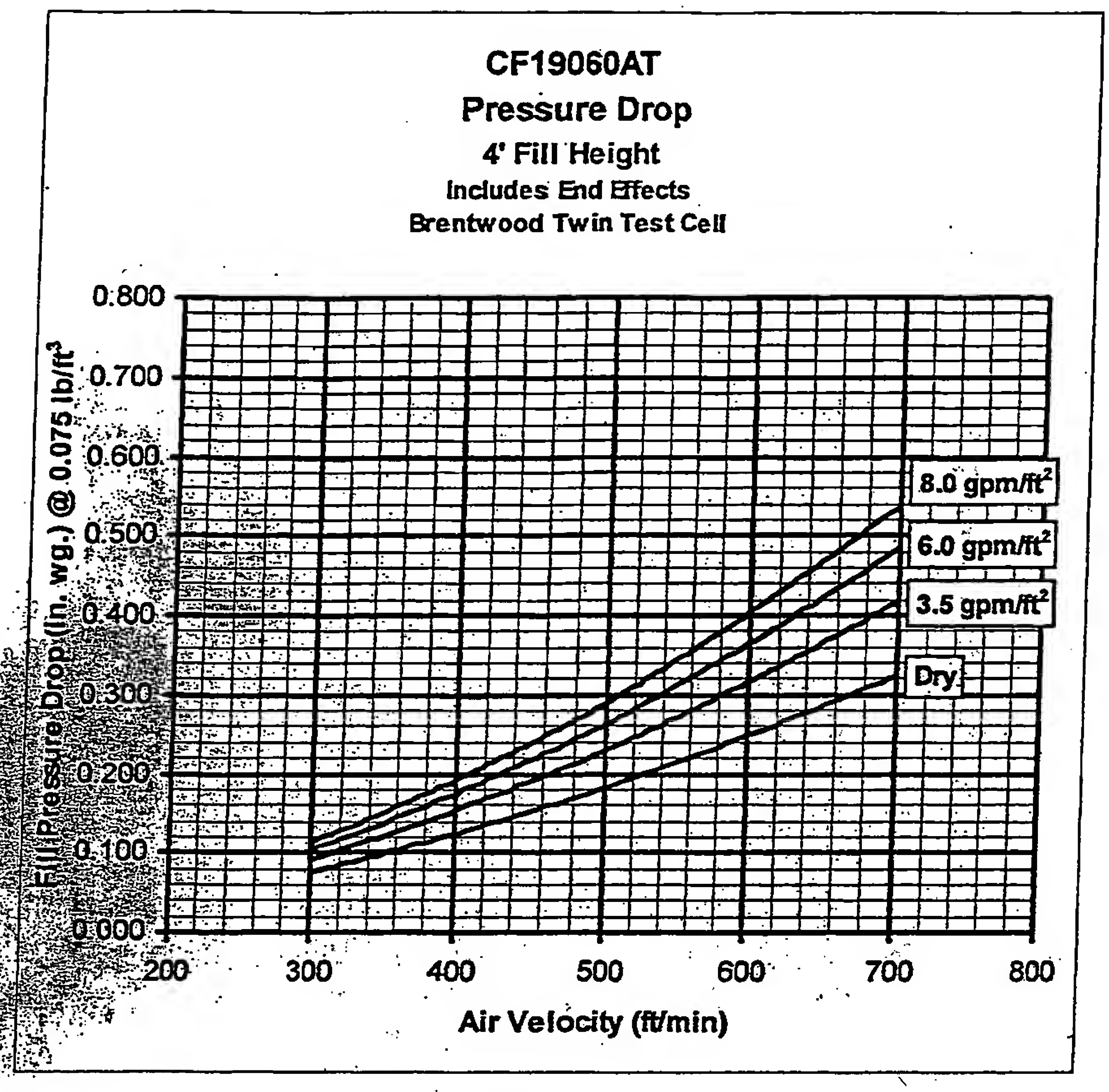

Figure 36.

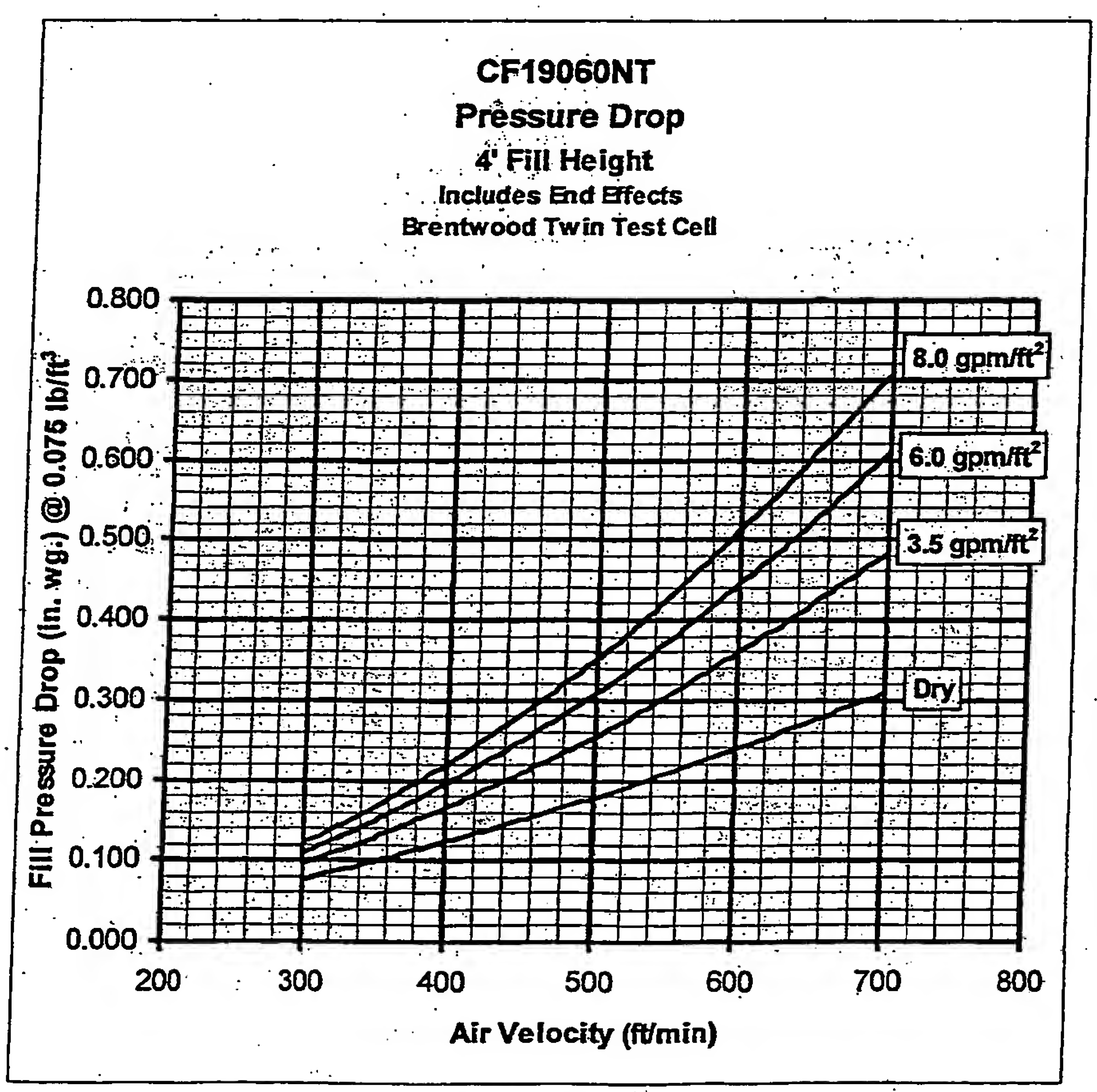

Figure 37.

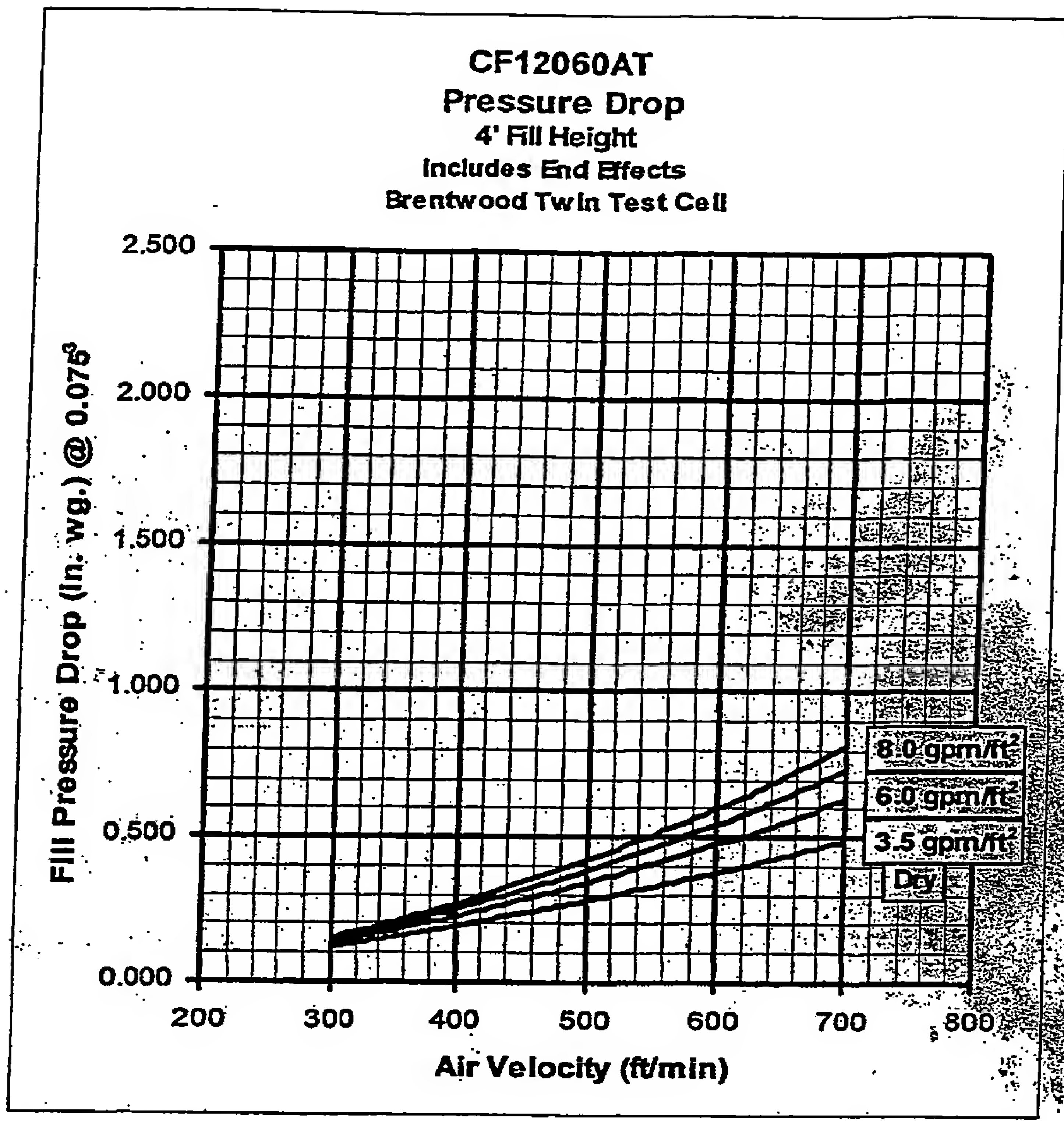

Figure 38.

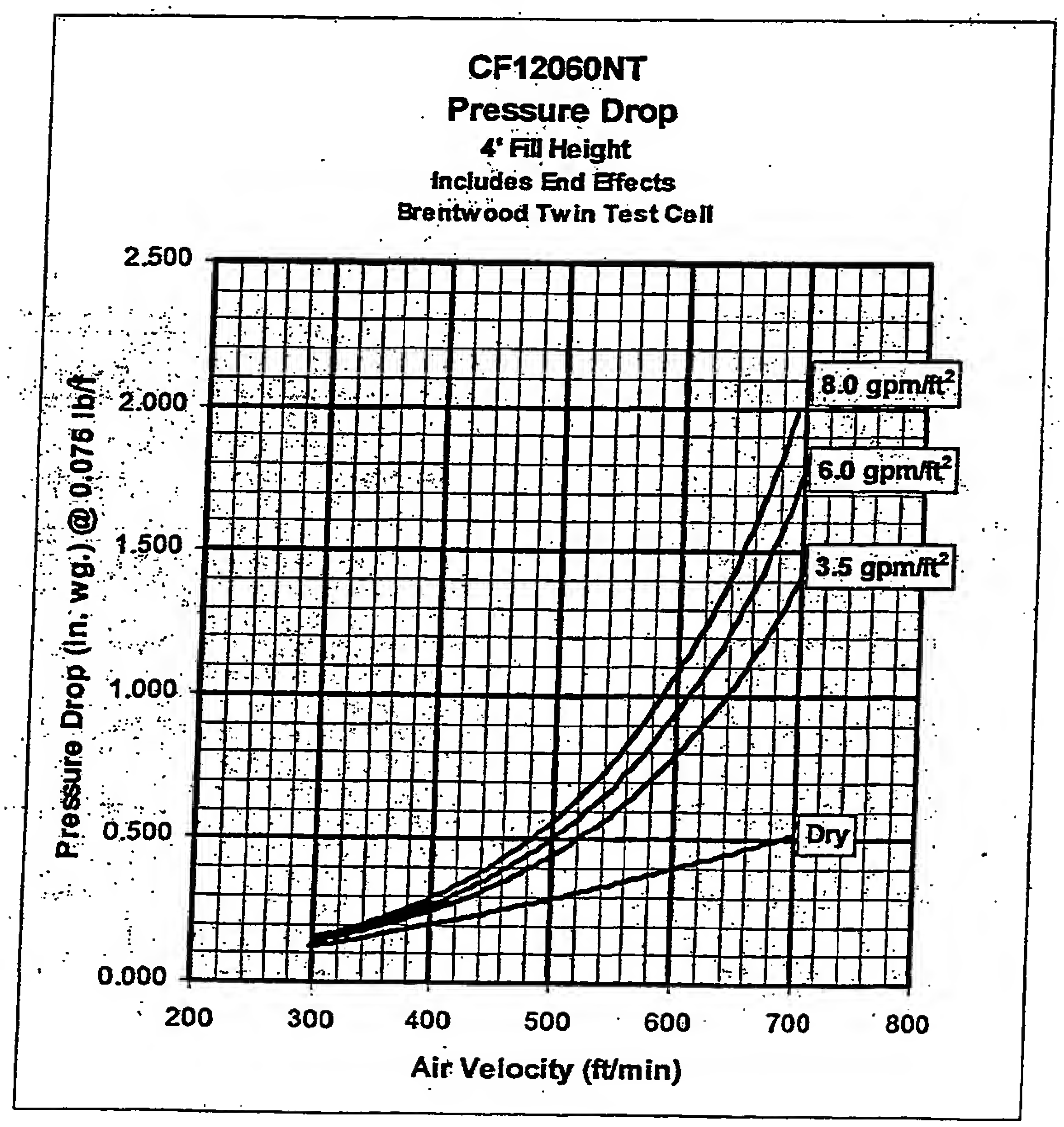

Figure 39.

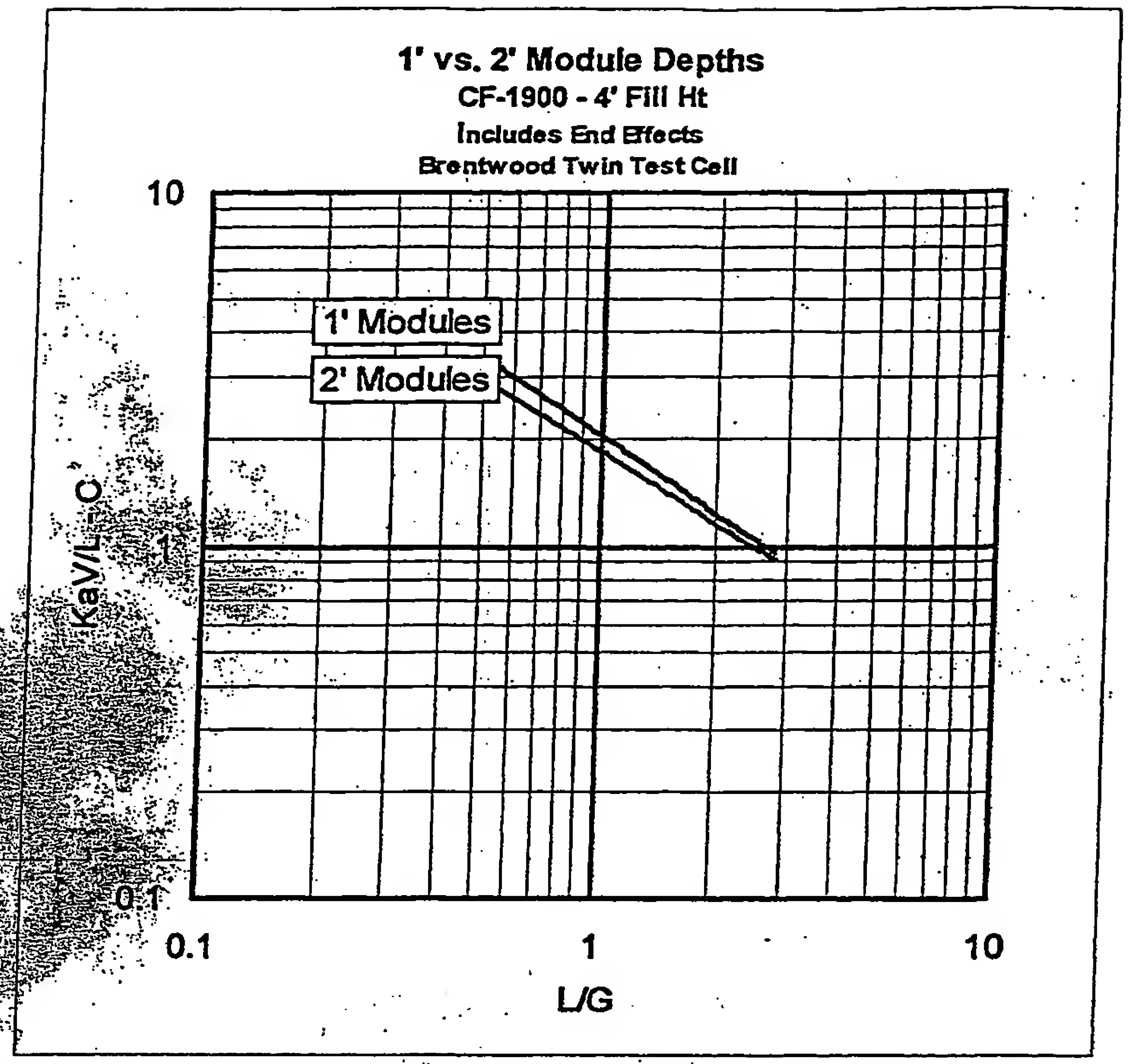

Figure 40.

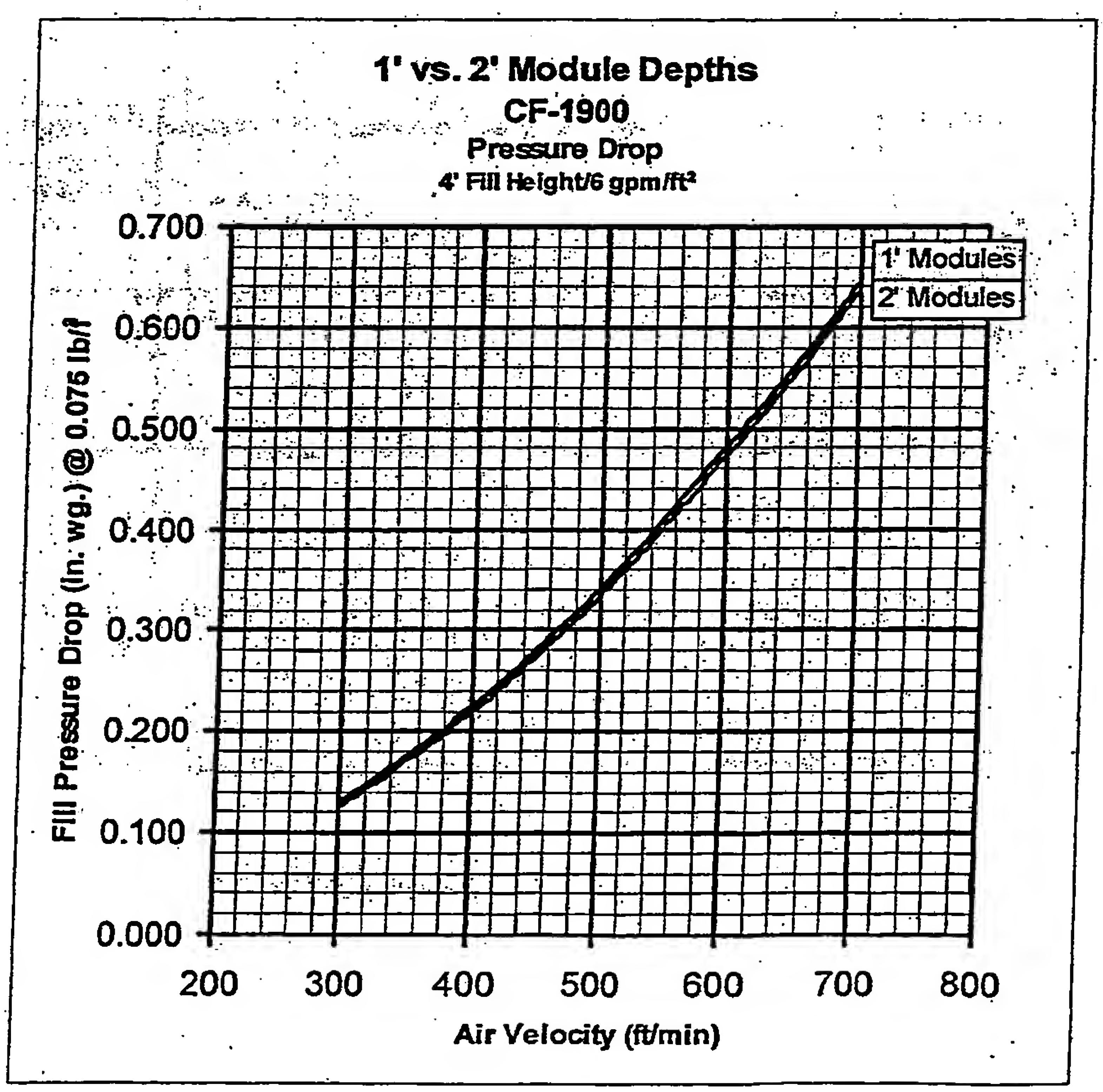

Figure 41.

CF Module Depth in. (mm)	q/a (gpm/ft^2)	l/g	Fill Vel (ft/min)	fill dp (in. wg.)	hp/1000ft^2	Capability (%)
12 (305)	3.5	1.016	414.0	0.206	13.7	100.0%
24 (610)	3.5	0.937	448.1	0.233	16.7	93.5%
12 (305)	6	1.445	503.8	0.327	26.7	100.0%
24 (610)	6	1.382	526.0	0.348	29.6	96.6%
12 (305)	8	1.904	514.7	0.365	30.7	100.0%
24 (610)	8	1.861	526.1	0.373	32.0	98.6%

Figure 42.

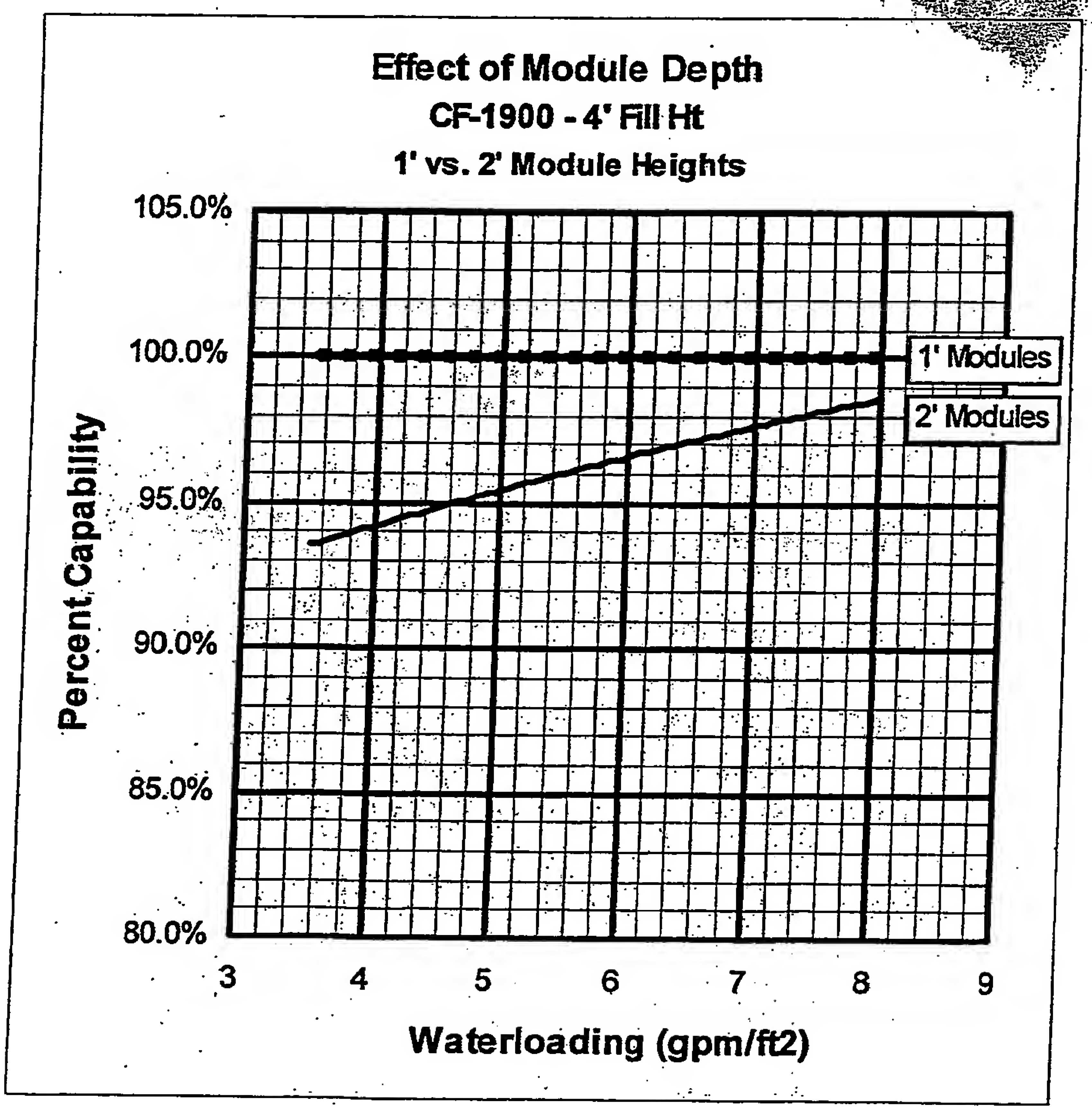

Figure 43.

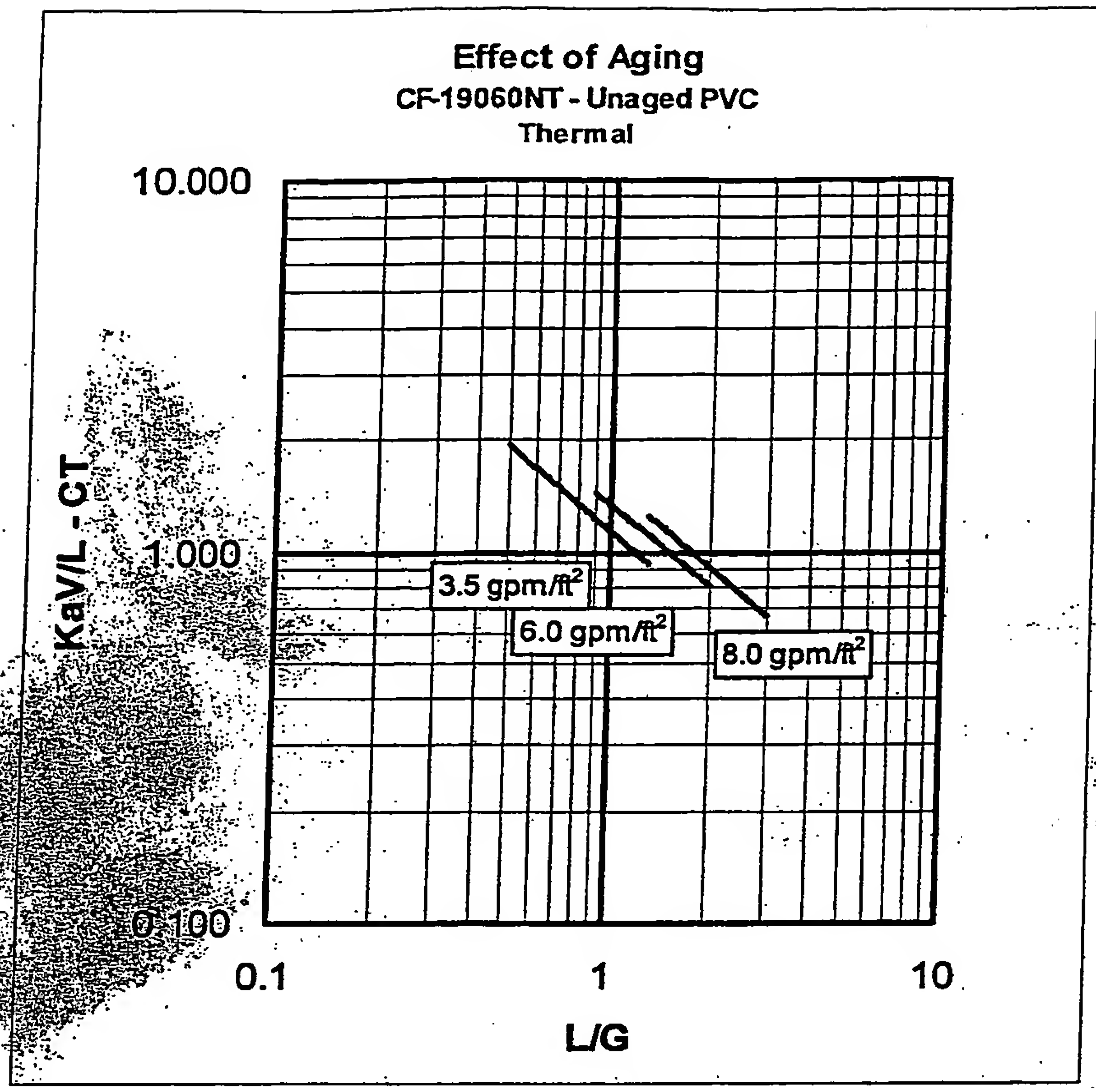

Figure 44.

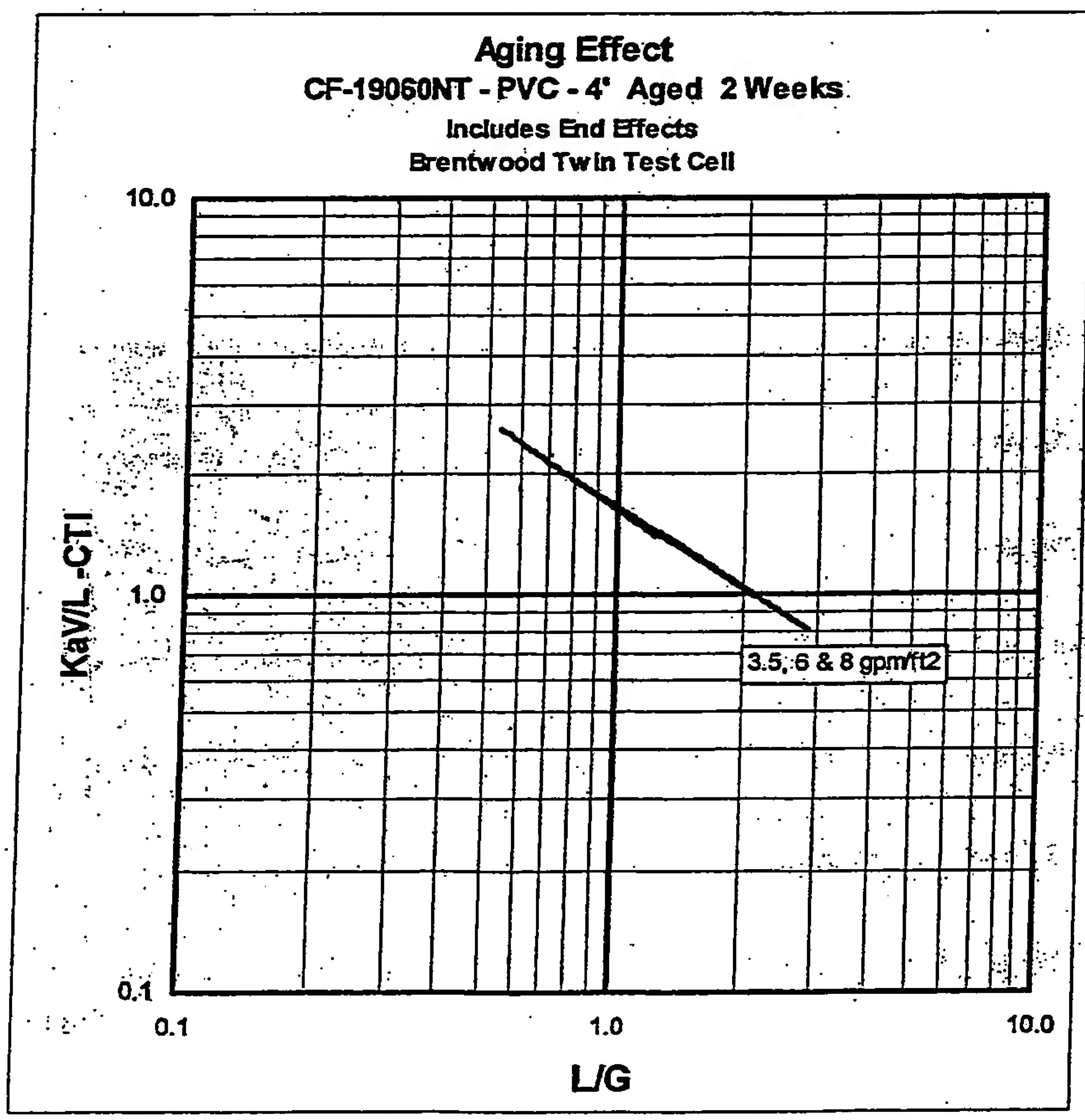

Figure 45.

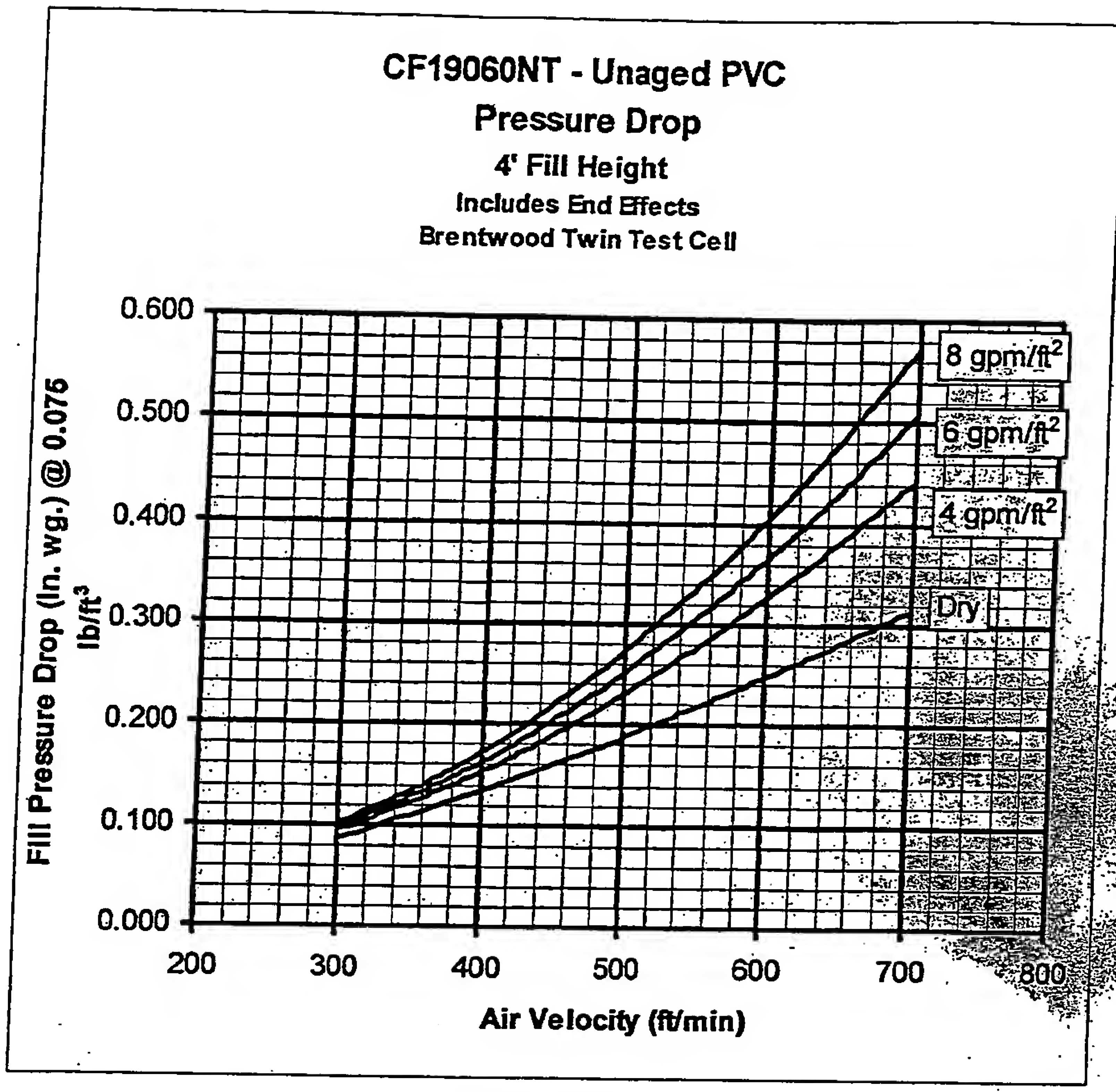

Figure 46.

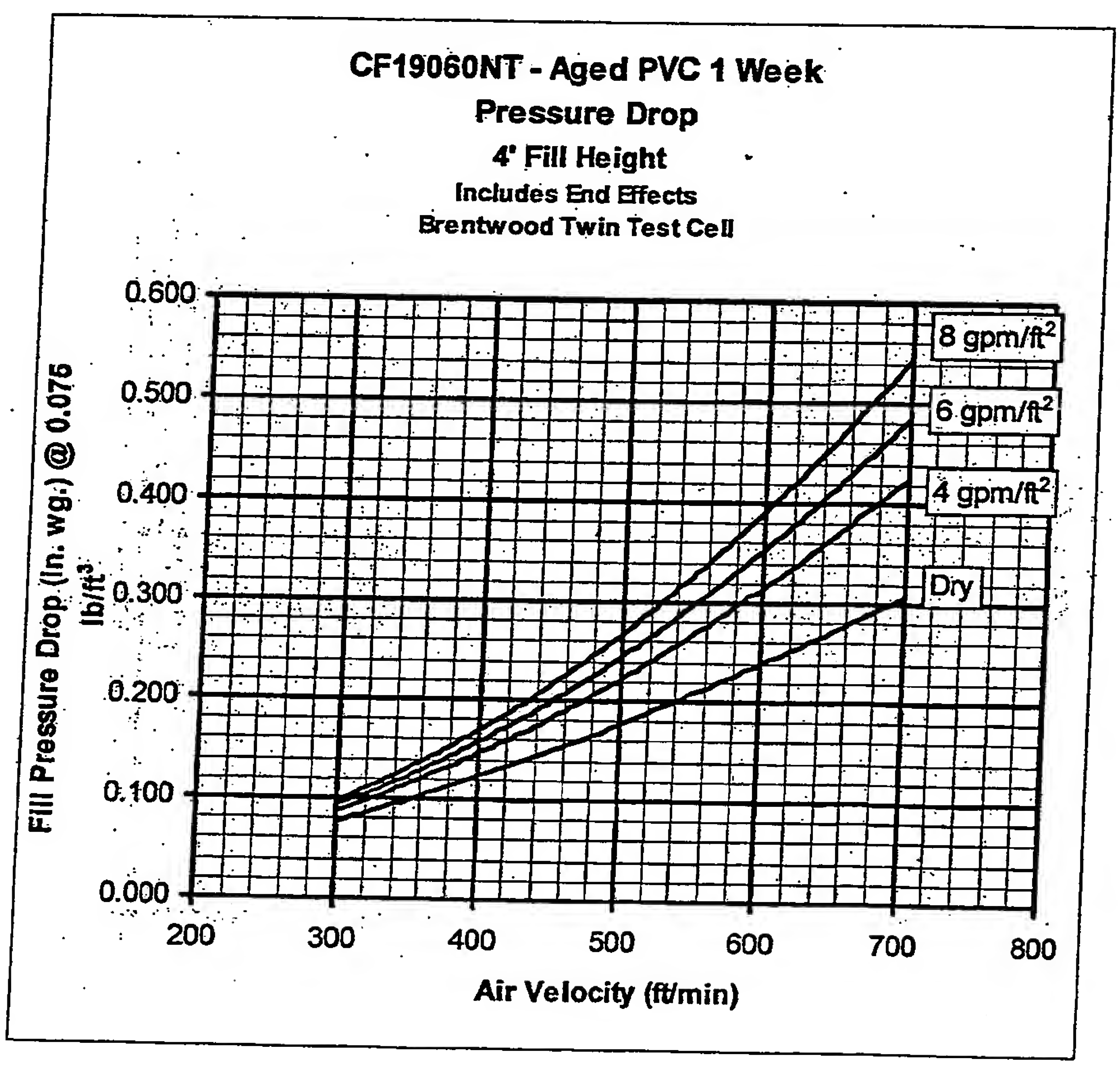

Figure 47.

19060NT PVC Weeks Aged	q/a (gpm/ft^2)	l/g	fill vel (ft/min)	fill dp (in. wg)	hp/1000ft^2	Capability (%)
0	3.5	0.642	649.1	0.360	37.1	75.0%
1	3.5	0.809	517.3	0.234	19.3	93.3%
2	3.5	0.871	481.2	0.204	15.7	100.0%
Full	3.5	0.871	481.2	0.204	15.7	100.0%
0	6	1.081	667.6	0.442	47.3	85.1%
1	6	1.212	597.4	0.351	33.7	95.3%
2	6	1.274	569.1	0.318	29.2	100.0%
Full	6	1.274	569.1	0.318	29.2	100.0%
0	8	1.591	611.6	0.439	43.6	90.5%
1	8	1.654	589.2	0.373	35.7	96.7%
2	8	1.711	570.3	0.348	32.3	100.0%
Full	8	1.711	570.3	0.348	32.3	100.0%

Figure 48.

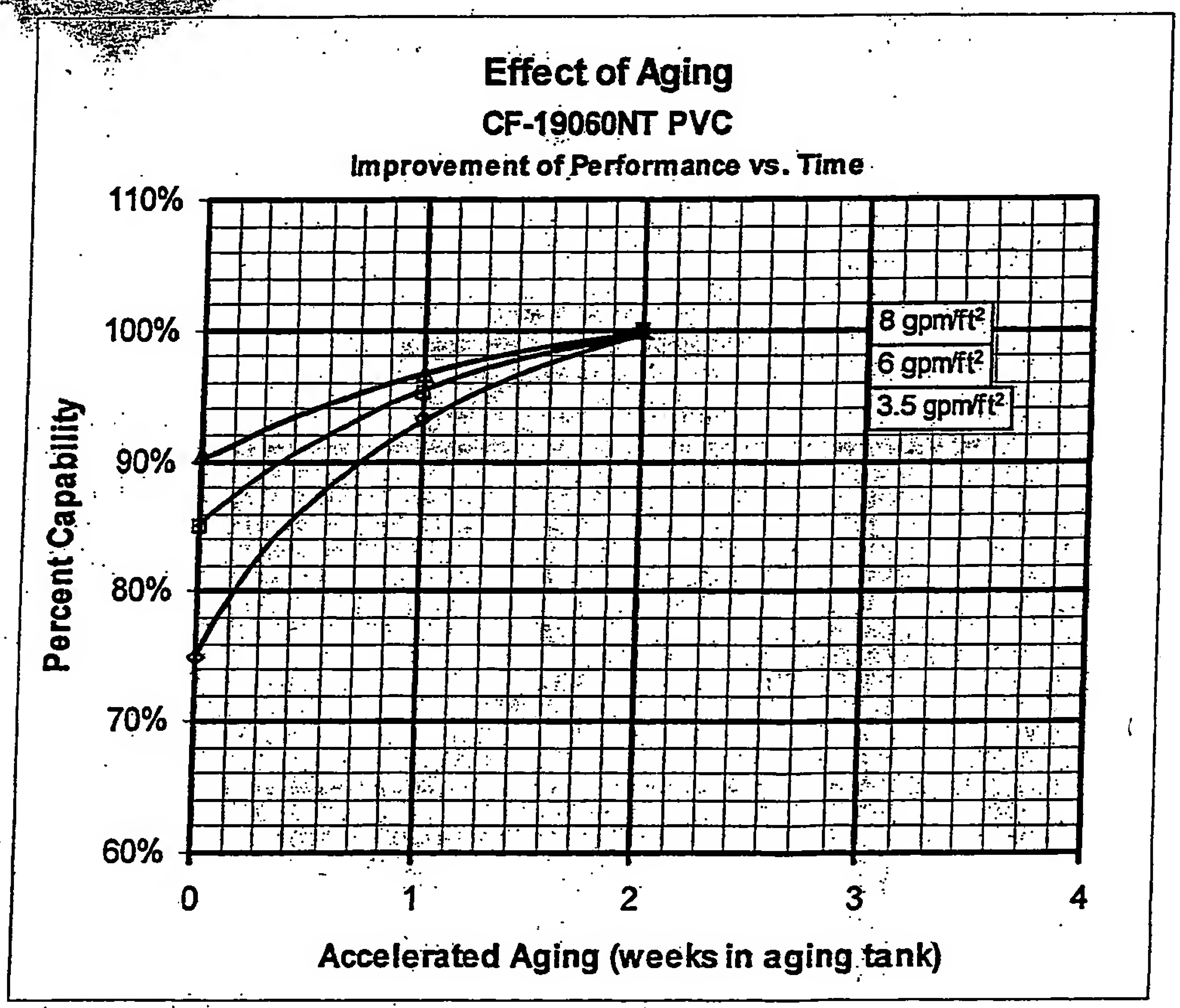

Figure 49.

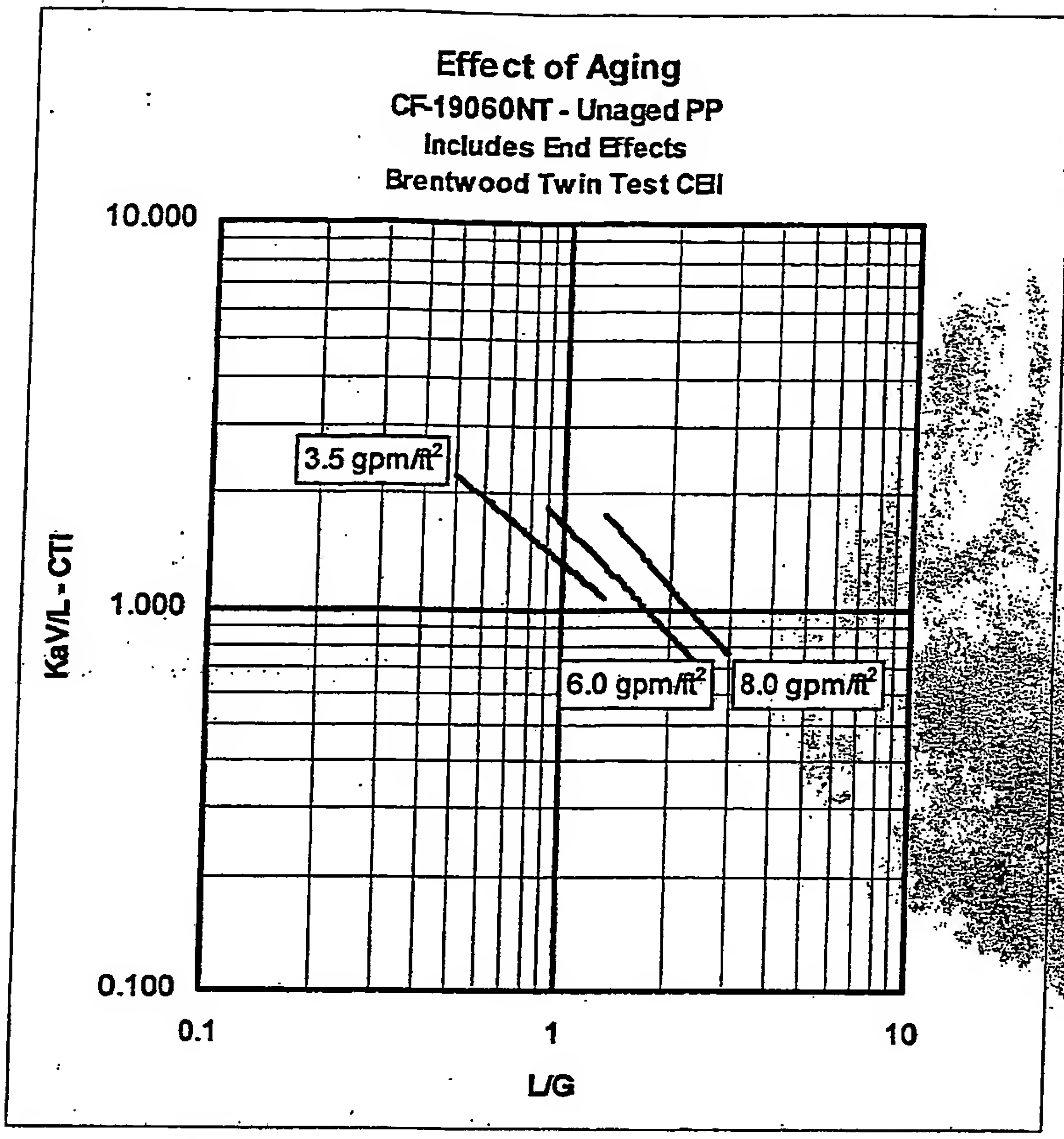

Figure 50.

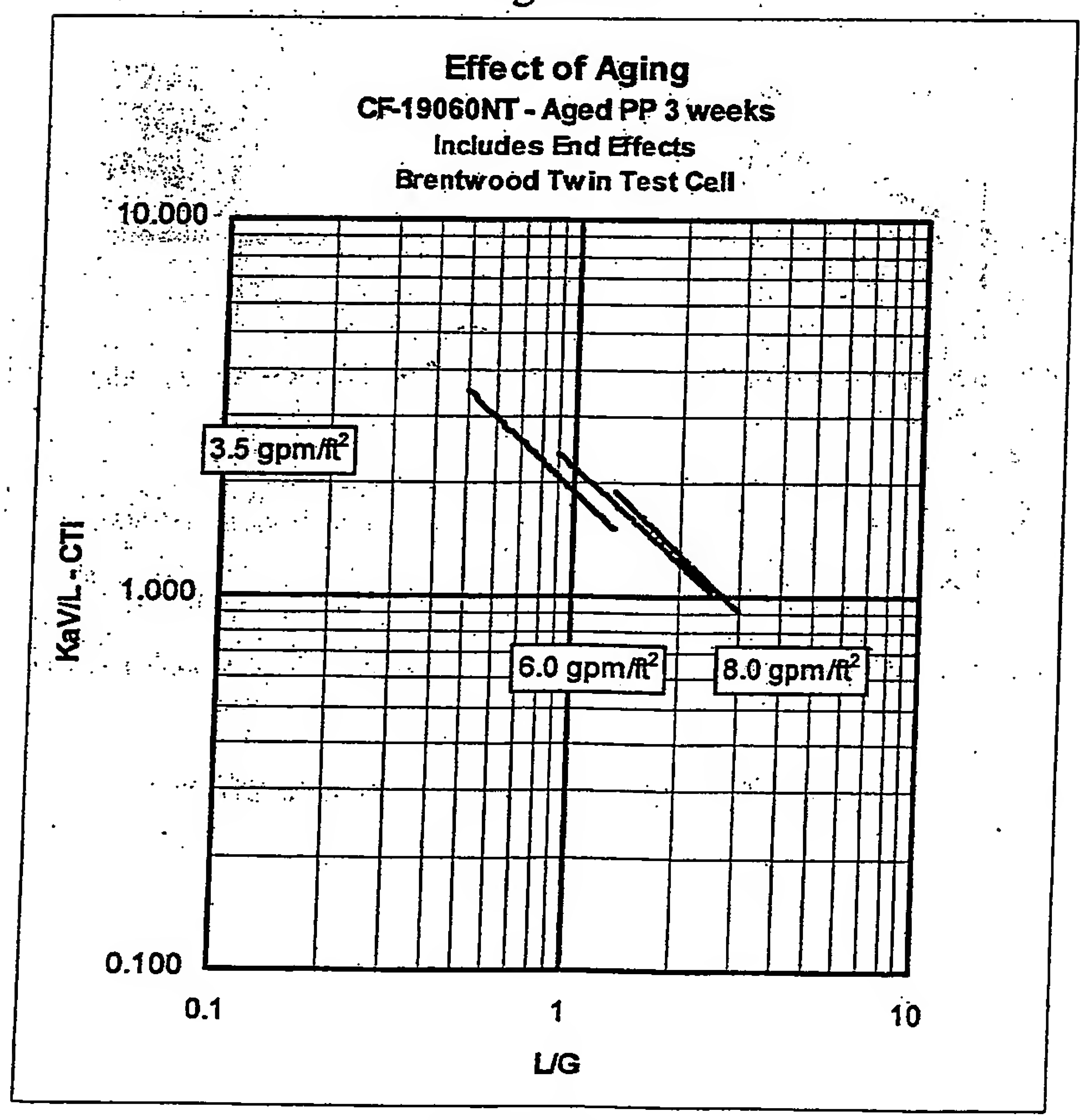

Figure 51.

19060NT-PP Weeks Aged	q/a (gpm/ft^2)	l/g	fill vel (ft/min)	fill dp (in. wg)	hp/1000ft^2	CWT (E)
0	3.5	0.724	576.8	0.578	53.0	67.0%
1	3.5	0.924	454.2	0.338	24.5	86.6%
2	3.5	0.963	436.3	0.311	21.7	90.2%
3	3.5	0.993	423.4	0.293	19.9	93.0%
Full	3.5	1.058	398.0	0.250	16.0	100.0%
0	6	1.229	589.3	0.694	65.8	78.5%
1	6	1.443	504.5	0.456	37.2	95.0%
2	6	1.467	496.5	0.438	35.2	96.8%
3	6	1.484	491.0	0.426	33.9	98.0%
Full	6	1.492	488.5	0.403	31.9	100.0%
0	8	1.852	528.5	0.544	46.9	92.4%
1	8	1.950	503.1	0.475	39.1	98.2%
2	8	1.956	501.6	0.471	38.6	98.6%
3	8	1.964	499.6	0.465	38.0	99.1%
Full	8	1.955	501.8	0.451	37.0	100.0%

Figure 52.

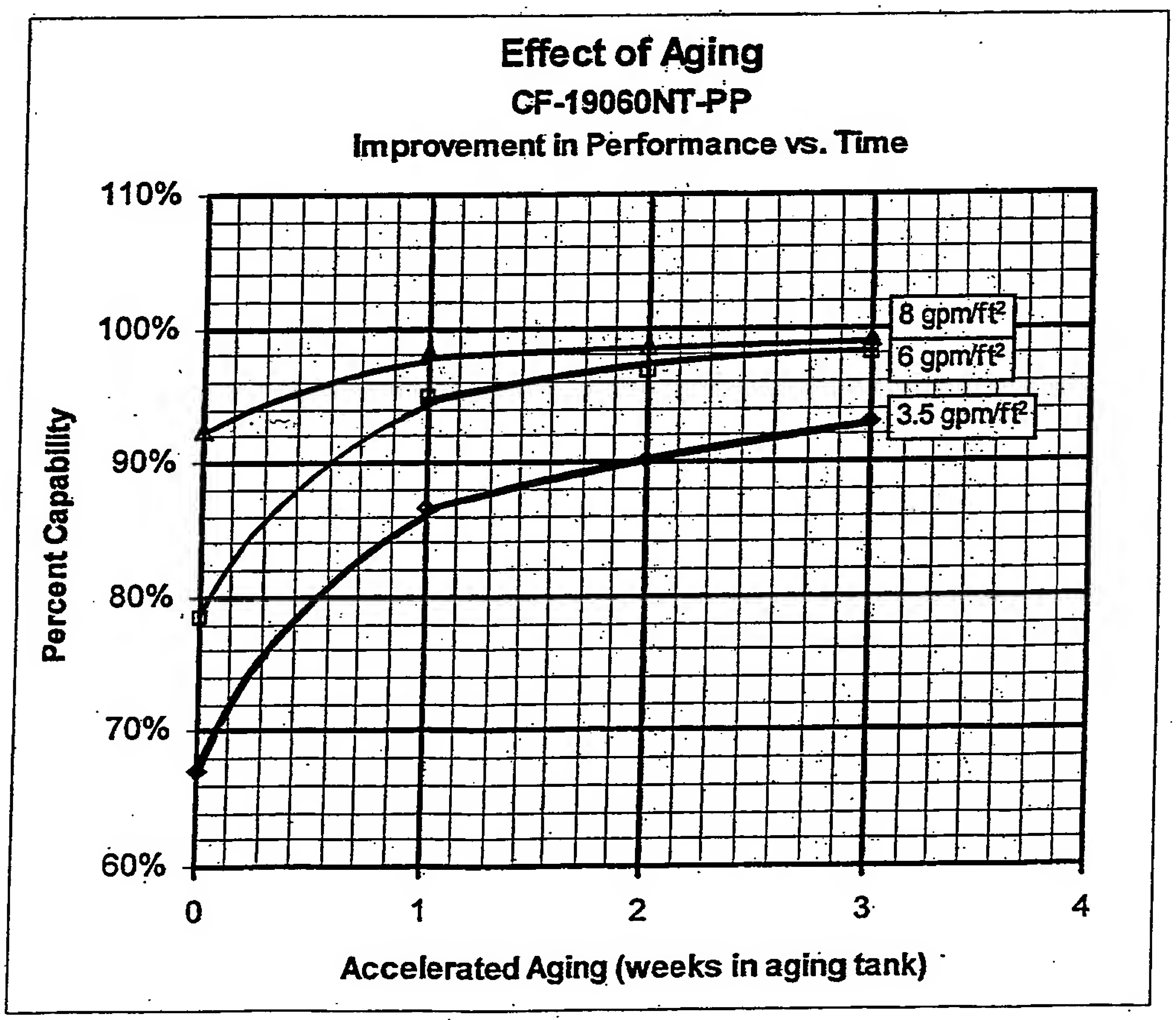

Figure 53.